UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Distr.
LIMITED
UNIDO/IO.580
6 April 1984
ENGLISH

HANDBOOK OF BIOMASS CONVERSION TECHNOLOGIES FOR DEVELOPING COUNTRIES*

Prepared by
Jean-Francois Henry, Abu Talib and Kathryn Ford
for the United States Department of Agriculture, Forest Service.
Made available to UNIDO
by the United States Agency for International Development.

---

*This document has been reproduced without formal editing. The views expressed in this paper are those of the authors and do not necessarily reflect the views of the secretariat of UNIDO.

P R E F A C E

The United Nations Industrial Development Organization as part of its mission to accelerate the industrialization of the developing countries conducts an active programme on energy development in relation to industry. Among the energy options available, biomass has a very significant potential for the developing countries and is an integral part of the UNIDO programme.

At the time we were contemplating the preparation of a handbook on biomass conversion technologies we learned that US AID had already done so and through the generous co-operation of Mr. Alan Jacobs this document was made available to UNIDO for reproduction and distribution.

Office of the Executive Director
UNIDO
May 1983

ACKNOWLEDGMENTS

This Handbook is addressed mostly to newcomers to the field of bioenergy and is designed to help them identify attractive and realistic bioenergy projects. It was prepared by Jean-Francois Henry of Warrenton, Virginia, and Abu Talib and Kathryn Ford, the MITRE Corporation, McLean, Virginia, under U.S. Department of Agriculture, Forest Service, Contract No. 53-319 R-2-65.

Many people provided valuable comments and suggestions at different stages of the publication of this Handbook. It was definitely a team effort involving the numerous authors of the state-of-the-art reports on conversion technologies. Valuable comments and suggestions were provided by Roscoe F. Ward, United Nations, New York, N.Y., Jack J. Fritz, National Academy of Sciences, Washington, D.C., Mr. Charles Bliss of US AID, Office of Energy and by George Beinhart, Pieter Hoekstra and Kjell Christophersen, members of the Bioenergy Systems and Technology group, USDA, Forest Service operating under a PASA with US AID Office of Energy.

To all these contributors and to those whom we did not mention by name, we express our deep gratitude.

W.Paul Weatherly
US AID - Office of Energy

H. Gus Wahlgren
USDA - Forest Service

FOREWORD

Bioenergy production systems are receiving considerable attention for the potential they hold for developing countries to meet their present and future energy needs independent of petroleum-derived fuels. However, when a developing country energy planner wishes to consider the potential offered by bioenergy, he is faced with a broad choice between bioenergy crops, conversion devices, and biomass-derived fuels. Moreover, a planner must accept greater economic and social risks because of the innovative nature of bioenergy technology.

Because of this need to help developing country planners make a careful consideration of bioenergy systems, the Office of Energy of the United States Agency for International Development (AID) Bureau for Science and Technology, in conjunction with the Forest Services and Office of Science and Education of the United States Department of Agriculture, has arranged for the preparation of this Handbook. It is intended to be used as a planning guide to help select the most appropriate bioenergy project for a developing country, given its need for a particular petroleum substitute and its bioresource production potential.

Alan B. Jacobs
Director, Office of Energy
U.S. Agency for International
Development

TABLE OF CONTENTS

Page:

INTRODUCTION 5

USER INSTRUCTIONS 9

BIOENERGY FUEL SUBSTITUTION INDEX AND DIRECTORY 14

SECTION A - BIOMASS TECHNOLOGY PRINCIPLES 15

- Anaerobic Digestion 16
- Direct Combustion 20
- Gasification 25
- Pyrolysis 32
- Char-Oil Slurry Combustion 38
- Hydrolysis 43
- Fermentation to Ethanol 47

SECTION B - INTERMEDIATE CONVERSION STEPS 50

- Steam Turbines 53
- Gas Turbine Engines 56
- Internal Combustion Engines 59
- Methanol Synthesis 62
- Mobil Synthesis 65
- Fischer-Tropsch Synthesis 68

SECTION C - BIOMASS TECHNOLOGY DATA 71

- Anaerobic Digestion 73
- Direct Combustion 84
- Small-scale Gasification 92
- Large-scale Gasification 100
- Pyrolysis 106
- Char-Oil Slurry Combustion 113
- Hydrolysis 118
- Fermentation to Ethanol 124

SECTION D - PETROLEUM-DERIVED ENERGY CONSUMPTION AND BIORESOURCE AVAILABILITY 133

- Table D-I: Country Data Index 134
- Table D-II: Petroleum-Derived Fuel Use Pattern, Ecuador 135
- Table D-III: Biomass Production, Ecuador 136

INTRODUCTION

Bioenergy refers to all fuels and energy products that can be produced from biological resources. Collectively, these resources are called "biomass." Table I lists typical biomass materials, conversion processes, and biomass-derived fuels and energy products that are useful direct or indirect substitutes for petroleum-derived fuels.

Direct substitutes here are defined as biomass fuels that can be used in place of petroleum-derived fuels without any further processing, although modifications in the existing energy conversion equipment may be required in some cases. Indirect substitutes are fuels which require either a new energy conversion system or further processing for use in place of petroleum-derived fuels.

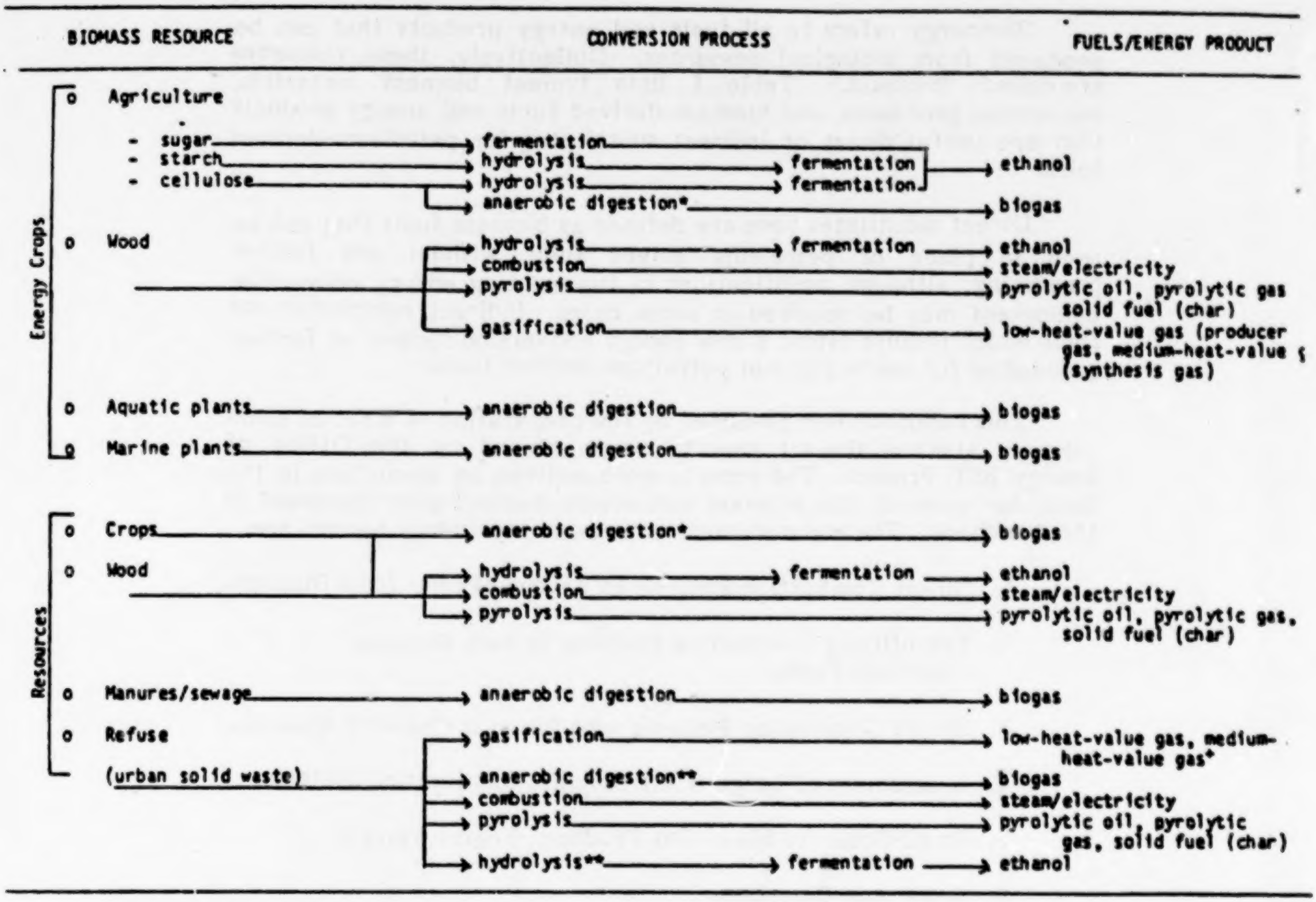
This handbook was preceded by the preparation of a set of some thirteen state-of-the-art reports commissioned by the Office of Energy BST Project. The reports were written by specialists in the field for each of the biomass conversion technologies discussed in this handbook. The commissioned conversion technology reports are:

1. Direct Combustion Systems to Produce Power from Biomass.
2. Retrofitting Combustion Systems to Burn Biomass-Derived Fuels.
3. Direct Combustion Systems with Biomass Char-Oil Mixtures.
4. Assessment of Large-Scale Biomass Gasification Systems.
5. Small-Scale (to 50kw) Gas Producer-Engine System.
6. Anaerobic Digestion.
7. Ethanol From Sugar Crops.
8. Status of Wood Hydrolysis for Ethanol Production.
9. Production of Methanol and its Derivatives from Biomass.
10. Pyrolysis of Wood and Agricultural Biomass.
11. Biomass-Fueled Heat Engines.
12. Designing Rural Cookstoves.
13. Report on Rural Industries.

Selecting a Bioenergy Project

Three factors affect the selection of a bioenergy project: its viability, implementability, and environmental impact. This

TABLE 1
BIOMASS CONVERSION PROCESSES AND FUELS/ENERGY PRODUCTS



	BIOMASS RESOURCE	CONVERSION PROCESS		FUELS/ENERGY PRODUCT
Energy Crops	o Agriculture			
	- sugar	→ fermentation		→ ethanol
	- starch	→ hydrolysis	→ fermentation	→ ethanol
	- cellulose	→ hydrolysis	→ fermentation	→ ethanol
		→ anaerobic digestion*		→ biogas
	o Wood	→ hydrolysis	→ fermentation	→ ethanol
		→ combustion		→ steam/electricity
		→ pyrolysis		→ pyrolytic oil, pyrolytic gas solid fuel (char)
		→ gasification		→ low-heat-value gas (producer gas, medium-heat-value (synthesis gas)
	o Aquatic plants	→ anaerobic digestion		→ biogas
	o Marine plants	→ anaerobic digestion		→ biogas
Resources	o Crops	→ anaerobic digestion*		→ biogas
	o Wood	→ hydrolysis	→ fermentation	→ ethanol
		→ combustion		→ steam/electricity
		→ pyrolysis		→ pyrolytic oil, pyrolytic gas, solid fuel (char)
	o Manures/sewage	→ anaerobic digestion		→ biogas
	o Refuse (urban solid waste)	→ gasification		→ low-heat-value gas, medium-heat-value gas+
		→ anaerobic digestion**		→ biogas
		→ combustion		→ steam/electricity
		→ pyrolysis		→ pyrolytic oil, pyrolytic gas, solid fuel (char)
		→ hydrolysis**	→ fermentation	→ ethanol

*Pretreatment required.
**Extensive preprocessing required.
+Can be used as feedstock for the synthesis of methanol or synthetic crude oil.

handbook contains data and information on biomass conversion technologies, which can be used in assessing these factors. Viability factors address issues of technology status, equipment, and biomass feedstock requirements; processing steps; cost competitiveness of bioenergy products versus conventionally used fuels; and markets for bioenergy products and fuels. Implementation factors address issues necessary to the use of the bioenergy technology and energy products, including local institutional support; project coordination with national goals and interests; extent of local manufacturing capability; available local technical skills; and transportation and distribution networks. Factors that relate to environmental impact consider land use, preservation of soil, multiple land use planning strategies, water preservation, water pollution, multiple use of water, and municipal and agricultural water needs, atmospheric pollution, air quality regulations, climate, and the overall effect on the human environment.

Assessment of these factors will differ for each country. In some cases it may not be possible to identify or quantify all the issues in a particular country. Situations must be considered individually to select appropriate projects, and considerable judgment based on experience needs to be exercised.

How this Handbook Is Organized

This book contains a Bioenergy Fuel Substitution Index and Directory to help the reader locate information in the four sections, which are:

Section A:	Biomass Technology Principles
Section B:	Intermediate Conversion Steps
Section C:	Biomass Technology Data
Section D:	Petroleum-derived Energy Consumption and Bioresource Availability.

Section A describes how biomass resources are converted into different fuels and energy products and how they may be used in a developing country. The major technical issues and problems associated with the respective biomass technologies are also highlighted.

Section B describes intermediate conversion steps used to convert some fuels and energy products obtained from biomass conversion processes into more useful energy forms. For example, steam derived from the combustion of biomass may be converted into electricity by means of a steam turbine. Conversion technologies such as a steam turbine are called intermediate conversion steps or processes and are applicable to fuels and energy products derived from both biomass and fossil fuels. The other intermediate conversion processes described in this section are: gas turbine engines, internal combustion engines, methanol synthesis, Mobil synthesis, and Fischer-Tropsch synthesis (indirect liquefaction).

Section C contains summary reviews of selected literature sources used by the authors in the preparation of the state-of-the-art reports listed in the Introduction. The summary reviews of each technology are referred to as entry statements. They are included in this handbook to provide the reader a concise reference. Readers seeking additional detailed information may refer directly to the state-of-the-art reports. Entry statements are organized according to whether the information relates to the technology's viability, implementation, or effect on the environment.

Section D contains tables illustrating the format for the presentation of petroleum-derived energy consumption and bioresource availability data for AID countries. One country, Ecuador is used as an example.

Several contractors are collecting these data for AID countries. As this data gathering is completed, tables containing relevant statistical information on AID countries will be made available for inclusion in this handbook.

The Bioenergy Fuel Substitution Index and Directory is the primary guide to the location of information about specific bioenergy fuel substitutes for petroleum-derived fuels. Readers will find references to specific pages in Sections A, B, and C containing information on both direct and indirect bioenergy substitutes.

USER INSTRUCTIONS

This handbook is organized according to the backgrounds and needs of four basic groups of users:

(1) those who are familiar with a country's energy consumption and resource availability and seek a bioenergy substitute for a particular petroleum-derived fuel in a particular sector

(2) those who are not familiar with a country's energy situation and do not have a particular sector/petroleum-derived fuel in mind. These are readers who seek to identify an appropriate bioenergy project for the country.

(3) those who have highly technical expertise and require data on a particular technology

(4) those who know the availability of a specific biomass resource in a country and may or may not have a particular sector/petroleum-derived fuel in mind. These are readers who seek the most effective use of the available resource as a substitute for petroleum-derived fuels.

Table II directs each group of users to the section most likely to answer their needs and describes briefly the kind of information that will be found there. Figure 1 presents essentially this same information in the form of a flow chart.

Table III shows the possible biomass-based fuels that may be derived from biomass energy sources. It will be useful for readers who know the biomass resource availability in a country and want to know possible biomass-based fuel substitutes.

The primary guide to the reader in this handbook is the Bioenergy Fuel Substitution Index and Directory. Those who have identified an energy consumption sector and petroleum-based fuel for potential bioenergy substitution will find a list of direct biomass-based substitutes and indirect biomass-based substitutes in columns 2 and 3. Having identified a substitute, the remaining columns direct the reader to the specific section and pages for detailed information about biomass technology principles (Section A), intermediate conversion processes or steps (Section B), and biomass technology data (Section C).

TABLE II
HOW TO FIND INFORMATION IN THIS HANDBOOK

USER PROFILE	WHERE TO LOOK IN THIS HANDBOOK	INFORMATION PROVIDED
You are familiar with a country's energy consumption and resource availability and seek a bioenergy substitute for a particular petroleum-derived fuel in a particular sector.	Bioenergy Fuel Substitution index: Columns 1 and 2	Direct and indirect bioenergy substitutes for petroleum-derived fuels.
	Column 3	The page number for a description of the bioenergy conversion technologies and major issues and problems associated with it. (Section A of this handbook)
	Column 4	The page number for a description of required (if any) intermediate conversion processes. (Column B of this handbook)
	Column 5	The page number for the technology data necessary to assess the feasibility of bioenergy projects. (Section C of this handbook)
You are not familiar with a country's energy situation and do not have a particular sector/petroleum-derived fuel in mind. You seek to identify an appropriate bioenergy project for the country	Section D: "Petroleum-Derived Energy Consumption and Bioresource Availability". See appropriate tables for the country interest.	Statistical data on a country-by-country basis. This data will help you select a particular sector/petroleum-derived fuel for potential bioenergy substitution.
	Bioenergy Fuel Substitution Index: Columns 1 and 2	Direct and indirect bioenergy substitutes for petroleum-derived fuels.
	Column 3	The page number for a description of the bioenergy conversion technology and major issues and problems associated with it. (Section A of this handbook)
	Column 4	The page number for a description of required (if any) intermediate conversion process. (Section B of this handbook)
	Column 5	The page number for the technology data necessary to assess the feasibility of bioenergy projects. (Section C of this Handbook).

TABLE II
HOW TO FIND INFORMATION IN THIS HANDBOOK
(CONCLUDED)

USER PROFILE	WHERE TO LOOK IN THIS HANDBOOK	INFORMATION PROVIDED
You have highly technical expertise and require data on a particular technology.	Section C: Biomass Technology Data	Contains selected technical data and information on promising bioenergy conversion technologies. Also contains references to other published materials that provide a more in-depth description of a particular technology.
You know the availability of a specific biomass reource in a country and may or may not have a particular sector/petroleum-derived fuel in mind. You seek the most effective use of the available resource as a substitute for petroleum-derived fuels.	Table III, "Fuels Derived from Biomass Resources," p. 9.	Lists fuels derived from each of several biomass resources. Note possible biomass fuel substitutes.
	If you do not have a sector/petroleum-derived fuel in mind, see Section D: "Petroleum--Derived Energy Consumption and Bioresource Availability". See appropriate tables for the country of interest.	Statistical data on a country-by country basis. This data will help you select a particular sector/petroleum-derived fuel for potential bioenergy substitution
	Bioenergy Fuel Substitution Index and Directory: Columns 1 and 2	Direct and indirect bioenergy substitutes for petroleum-derived fuels.
	Column 3	The page number for a description of the bioenergy conversion technology and major issues and problems associated with it. (Section A of this handbook)
	Column 4	The page number for a description of required (if any) intermediate conversion process. (Section B of this handbook)
	Column 5	The page number for the technology data necessary to assess the feasibility of bioenergy projects. (Section C of this handbook)

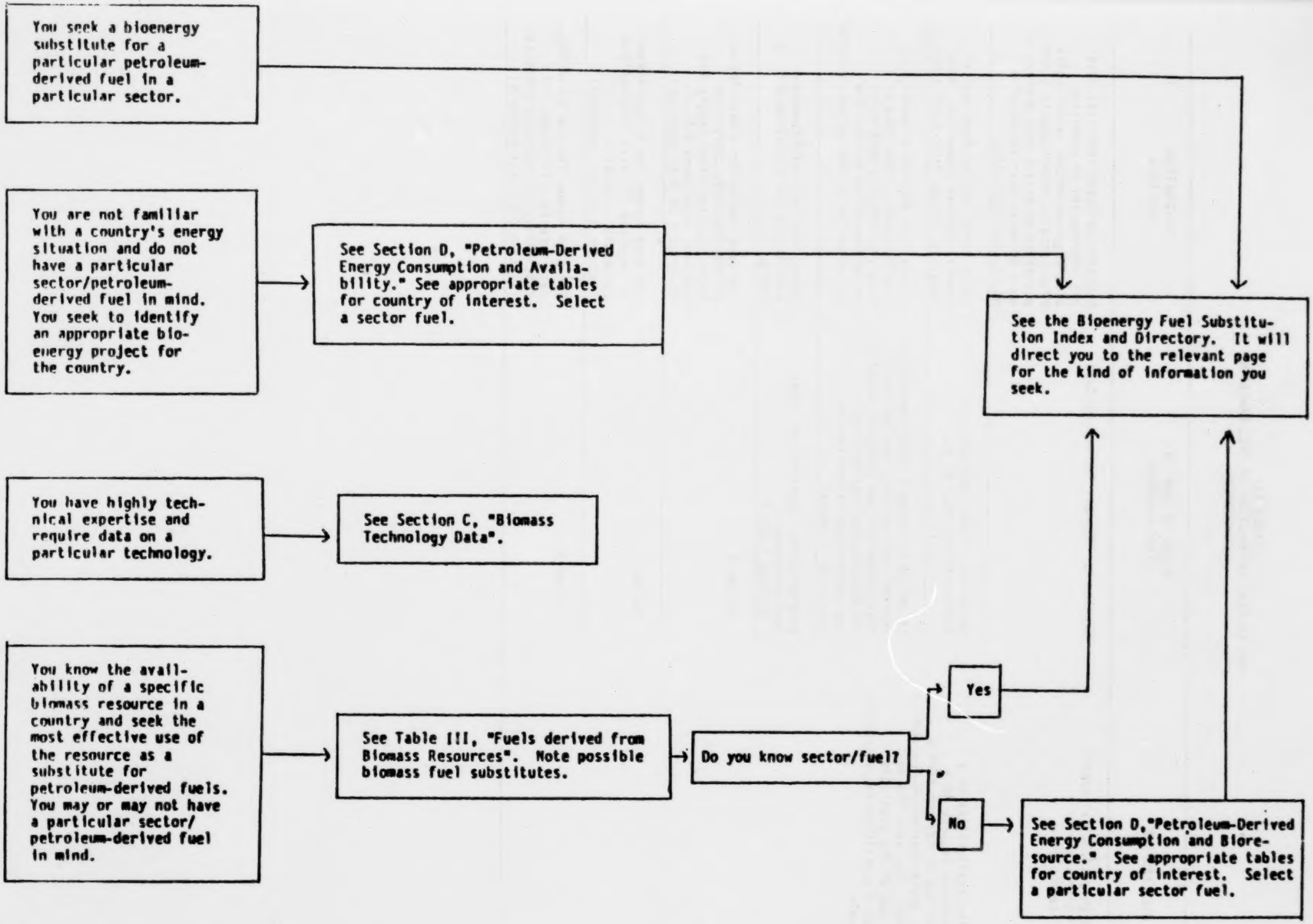

You seek a bioenergy substitute for a particular petroleum-derived fuel in a particular sector.
You are not familiar with a country's energy situation and do not have a particular sector/petroleum-derived fuel in mind. You seek to identify an appropriate bioenergy project for the country.
See Section D, "Petroleum-Derived Energy Consumption and Availability." See appropriate tables for country of interest. Select a sector fuel.
See the Bioenergy Fuel Substitution Index and Directory. It will direct you to the relevant page for the kind of information you seek.
You have highly technical expertise and require data on a particular technology.
See Section C, "Biomass Technology Data".
You know the availability of a specific biomass resource in a country and seek the most effective use of the resource as a substitute for petroleum-derived fuels. You may or may not have a particular sector/petroleum-derived fuel in mind.
See Table III, "Fuels derived from Biomass Resources". Note possible biomass fuel substitutes.
Do you know sector/fuel?
Yes
No
See Section D, "Petroleum-Derived Energy Consumption and Bioresource." See appropriate tables for country of interest. Select a particular sector fuel.

FIGURE 1
HOW TO FIND INFORMATION IN THIS HANDBOOK

TABLE III
FUELS DERIVED FROM BIOMASS RESOURCES

BIOMASS RESOURCE	BIOMASS-DERIVED FUELS
Manures High moisture feedstocks (aquatic and marine plants) Crop residues* Municipal solid waste*	Biogas
Wood Wood residues Crop residues Municipal solid waste	Producer gas (low-heat-value gas) Pyrolytic gas Medium-heat-value gas (synthesis gas) Pyrolytic oil Char Solid fuels** Synthetic crude*** Methanol*** Ethanol$^+$
Starch and sugar crops	Ethanol

* Preprocessing steps are required

** Examples include pelletized wood and wood chips.

*** Produced form biomass-derived synthesis gas.

+ Hydrolysis is required.

BIO-ENERGY FUEL SUBSTITUTION INDEX AND DIRECTORY

SECTOR/FUEL	BIOMASS FUEL		PAGE NUMBER FOR		
	1 DIRECT SUBSTITUTE*	2 INDIRECT SUBSTITUTE**	3 SECTION A BIOMASS TECHNOLOGY PRINCIPLES	4 SECTION B INTERMEDIATE CONVERSION PROCESS	5 SECTION C BIOMASS TECHNOLOGY DATA
RESIDENTIAL					
LPG	BIOGAS		A-3		C-101
KEROSENE	BIOGAS		A-3		C-101
ALL FUELS***		SOLID FUEL SYNTHETIC CRUDE	A-7 A-12	B-18	
TRANSPORT					
GASOLINE	ETHANOL METHANOL LOW-HEAT-VALUE GAS†	METHANOL	A-30, A-34 A-12 A-12 A-12	B-9 B-12 B-9 B-12, B-15	C-701, C-801 C-301
DIESEL††	LOW-HEAT-VALUE GAS†		A-12	B-9	C-301
ALL FUELS		SYNTHETIC CRUDE	A-12	B-18	
INDUSTRIAL					
RESIDUAL FUEL OIL	PYROLYTIC OIL CHAR-OIL SLURRY LOW-HEAT-VALUE GAS†		A-19 A-25 A-12		C-501 C-601 C-401
DIESEL††	LOW-HEAT-VALUE GAS†		A-12	B-6, B-9	C-401
LPG	LOW-HEAT-VALUE GAS†		A-12	B-6, B-9	C-401
ALL FUELS***		SOLID FUEL SYNTHETIC CRUDE	A-7 A-12	B-18	C-201
ELECTRICITY GENERATION					
RESIDUAL FUEL OIL	PYROLYTIC OIL CHAR-OIL SLURRY LOW-HEAT-VALUE GAS†		A-19 A-25 A-12	B-3 B-3 B-3	C-501 C-601 C-401
DIESEL††	LOW-HEAT-VALUE GAS† BIOGAS		A-12 A-3	B-6, B-9 B-9	C-401 C-101
LPG	BIOGAS		A-3	B-9	C-101
ALL FUELS***		SOLID FUEL SYNTHETIC CRUDE	A-7 A-12	B-3 B-18	C-201

*Direct substitutes are biomass fuels that can be used in place of petroleum-derived fuels without any further processing, although modifications in existing equipment might be required in some cases.

**Indirect substitutes are fuels that require either a new energy conversion system or further processing in order to be used in place of petroleum-derived fuels.

***Refers to petroleum-derived fuels.

†Also known as producer gas.

††Also applies to distillate fuel oil.

SECTION A

BIOMASS TECHNOLOGY PRINCIPLES

This section describes how biomass resources are converted into fuels and energy products and used. Highlights of the current status, issues, and problems for each technology are also presented. The section on each technology includes:

1. **Definition**
2. **Technical Description**
3. **Current Status of the Technology**
4. **Technology Issues and Problems**
5. **Future Development**
6. **Product(s) Utilization**

ANAEROBIC DIGESTION
A Technology to Produce Biogas

1. Definition

Anaerobic digestion is a biological process in which organic matter in the absence of oxygen is converted to a mixture of methane and carbon dioxide, sometimes called biogas. This process occurs naturally in fresh water and marine sediments, flooded soils, and landfills. It can also take place in industrial and municipal waste treatment operations. Biomass feedstocks used in facilities designed for methane production include human and animal wastes and crop residues.

2. Technical Description

Anaerobic digestion is a three-stage process requiring the presence of certain types of bacteria. In the first stage, bacteria convert the digestible fraction of the bioresource into fermentable short-chain fatty acids. Hydrogen-producing bacteria then use these acids to produce acetate, carbon dioxide, and hydrogen. Finally, methane-producing bacteria use acetate, hydrogen, and carbon dioxide to produce a methane-rich (more than 50 percent) biogas. Specifically, these bacteria cleave acetate to yield methane and carbon dioxide, and they use hydrogen and carbon dioxide to yield additional methane.

In the presence of methane-producing bacteria, the consumption of hydrogen produced in the first and second stages is almost instantaneous, and hydrogen is not present in the product gas. If hydrogen is detected, methane formation in the third stage is not occurring efficiently. This usually happens when the bacterial growth is disturbed.

Methane-producing bacteria require a specific environment for growth. They are inhibited by small amounts of oxygen. The fermentation process is influenced by :

- temperature
- pH
- loading rate/retention time
- mixing
- recycling/dilution
- presence of substances that may be toxic to the bacteria and thereby hinder the biochemical reactions
- nutrients

Parameters must be kept within acceptable limits to maintain stable digester operation. However, it is also important to weigh the economics of digester construction and operation against increased process stability, efficiency, and methane production.

The digester is the container in which methane is produced. For a detailed discussion of digester designs and the factors listed previously, see the original state-of-the-art report.(1)* However, quantitative data as extracted from the selected literature sources used to prepare the state-of-the-art report on methane fermentation technology are presented in Section C of this handbook.

3. Current Status of the Technology

Biomass (animal manure, crop residues, night soil, etc.) for production of a methane-rich (greater than 50 percent by volume) fuel gas via anaerobic digestion has been utilized in several parts of the world for many years. In countries such as India, the People's Republic of China, the Republic of Korea, Taiwan, and Thailand, government programs have led to the construction of small-scale anaerobic digestion units.

---

* Numbers in parentheses refer to numbered references listed at the end of this subsection.

These small-scale units are used to supply the cooking and lighting energy needs of rural families, particularly in India and China. Large-scale community digesters are also operating in several developing countries to supply the energy needs of several rural families.

Anaerobic digestion as a waste treatment process for sewage has been used for nearly a century in several parts of the world. The main function of anaerobic digestion is waste stabilization. However, the by-product methane-rich fuel gas (biogas) is increasingly being used to supply part of the energy needs of the waste treatment plant.

4. Technology Issues and Problems

Even though anaerobic digestion is an old and proven technology, process design for efficient energy production is not fully understood, and research and development work is under way to improve efficiency, reliability, and applicability to other biomass feedstocks. Descriptions of potential technical, environmental, economic, social, and institutional problems associated with this technology follow. For quantitative data on these factors, see Section C of this handbook. Detailed discussions are presented in the state-of-the-art report(1) and in Wise.(3)

o Technical. The technology of anaerobic digestion is primarily linked to the treatment of wastewater and manure slurries. Extensive operating experience has been accumulated in developing countries on both family- and community-size anaerobic digestors using animal waste as the primary feedstock. Also, several large-scale manure digesters are successfully operating in the U.S. Process development activities are currently underway at several institutions around the world to develop improved anaerobic digestion techniques for feedstocks such as seaweed, algae, agriculture residue, and municipal solid waste.

Although family-size anaerobic digesters are successfully operating in the rural settings of both China and India, technical problems, particularly in India, have caused operational difficulties. The major technical problems are: (1) corrosion of steel gas holders; (2) lower gas production in winter months when energy requirements are the greatest; (3) feedstock material and effluent handling; and (4) cracking of digester walls. The problems, in part, can be solved either by design modifications or alternative design configurations (i.e., Chinese design).

o Environmental. The environmental impacts of disposal of the effluents of anaerobic digesters are significantly less than that of the original feedstocks (manure, human wastes, organic wastes, etc.). However, proper management of effluent streams is important in controlling pollution. For case-specific information on these problem areas, turn to Section C of this handbook.

o Socioeconomic and Institutional. Although anaerobic digestion has been successful in the rural areas of some developing countries, certain social and economic problems have limited its adoption. This is particularly true for the rural areas of India, where the socioeconomic problems encountered include (1) high cost of plants, thus not affordable by poor rural families, (2) lack of space for installation of plants in the poorer sections of the village because of clustering of houses, (3) the traditional toilets - users preferences, and (4) people's unawareness of the benefits of biogas.

For specific information on these factors see Section C of this handbook. Detailed discussions can be found in the state-of-the-art report.(1)

5. Future Development

Advances in anaerobic digestion technology will focus on the development of less expensive small family- and community-size digesters. These less expensive designs will use low-cost materials, such as rubber-like liner materials, and earth-supported structure, for digester construction.(2) Also, pretreatment techniques are being developed so that cellulosic feedstocks (crop residues, municipal solid waste) can be efficiently and economically converted to biogas. Economical and reliable harvesting techniques are being developed for feedstocks such as aquatic biomass. These bioresources are being considered for large commercial-scale anaerobic digestion systems to produce a substitute natural gas that is pipeline quality.

6. Product(s) Utilization

The products of anaerobic digestion typically consist of 50 percent or more methane and carbon dioxide with trace amounts of hydrogen sulfide, ammonia, and nitrogen. The exact composition of gas is a function of the feedstock and the operating conditions. Details regarding the composition and heating value of the gas for various feedstocks and operating environments can be found in Section C of this handbook.

o Biogas as a Fuel for Cooking and Lighting. As mentioned earlier, biogas from small-scale anaerobic digesters is used as a cooking and lighting fuel in rural areas of several developing countries, particularly in China and India. Fairly reliable stoves are available for using biogas as a cooking fuel. For example, simple burners consisting of iron pipes closed at one end and perforated along their lengths with one or two rows of holes are made in villages by local blacksmiths. The holes are typically 3.2 mm to 4.8mm (1/8 in. to 3/16 in.) in diameter and 12.7 mm to 19.1 mm (1/2 in. to 3/4 in.) apart.

For lighting, biogas can be fed to any gas lamp using a mantle. However, the light is usually not very bright because the lamps are generally made to use gas at 7.6 cm (3 in.) water column pressure. These lamps cannot be satisfactorily used with small digester plants which have a gas pressure of 2.5 cm to 3.8 cm (1 in. to 1.5 in.) of water column. Quantitative data on the biogas consumption for cooking and lighting are presented in the Section C of this handbook.

o Biogas as a Fuel for Internal Combustion. Pure methane is an ideal fuel for internal combustion engines. Since biogas contains more than 50 percent methane, it can be burned in existing internal combustion engines after minor modifications. This is particularly true with gasoline engines. However, conversion of existing diesel engines to burn 100 percent biogas is more difficult. A more practical way is to convert the conventional diesel engine to dual-fuel firing. Dual-fuel engines can use a mixture of biogas and diesel oil (90 percent biogas and 10 percent diesel). In actual practice, biogas is used as the main fuel with diesel oil as a startup fuel.

In the rural areas of developing countries, diesel engines are the most widely used internal combustion engines. Diesel engines are typically used to power irrigation pumps, to run electric generators for small-community power generation and to run grain mills. In these operations, biogas can be substituted for diesel oil by retrofitting existing engines. Technical descriptions of diesel and dual-fuel engines are presented in Section B of this handbook. For quantitative data on biogas in diesel or dual-fuel engines, see Section C.

o Possible Uses of Digested Sludge. During the anaerobic digestion processes, most of the unconverted solids settle out in the digester as a liquid sludge. Depending on the feedstock and the operating conditions of the digester, the sludge may contain many elements essential to plant life. Thus, digested sludge is considered an excellent source of fertilizer and soil conditioner. However, the handling of this material as liquid sludge is difficult. Sludge can be used:

— directly, after diluting with water

— after drying

— as a starter for compost

— as a manure concentrate when enriched with urea and superphosphates

Relevant data on the use of digested slurry can be found in Section C.

References

1. Anaerobic Digestion: Biogas Production and Use. AID Office of Energy, Washington, D.C. (in preparation).

2. Anaerobic Fermentation of Agricultural Residue: Potential for Improvement and Implementation, W. J. Jewell et al., Cornell University, New York, N.Y.

3. Fuel Gas Production from Biomass, Volumes I and II, D. L. Wise, Editor, CRC Press, Boca Raton, Florida, 1981.

DIRECT COMBUSTION
A Technology to Produce Heat and/or Steam

1. Definition

Direct combustion of biomass is the burning of the material in the presence of an excess quantity (more than stoichiometric* amount) of air. During this process, a rapid chemical reaction of oxygen from the air with the combustible elements of biomass feedstocks takes place, accompanied by rapid production of heat.

2. Technical Description

The major combustible elements present in biomass feedstocks are carbon and hydrogen. The amount of oxygen available for combustion primarily controls the rate of burning. In practice, a quantity of oxygen in excess of that theoretically required to burn the combustible fraction of biomass feedstocks is used to ensure complete combustion. The oxygen source of combustion is usually air.

Low-moisture (less than 50 percent**) biomass feedstocks like wood, wood residue, and crop residues are ideal fuels for direct combustion. Feedstocks containing higher moisture (more than 50 percent) content can be burned less efficiently or may be predried before combustion, or auxiliary conventional fuels can be used to assist in the combustion of relatively wet fuels. Pyrolytic char (see Pyrolysis in this section) of proper quality can also be used as a fuel for direct combustion.

During combustion, biomass fuels (or feedstock) initially are heated to a temperature high enough to drive off the water in the fuel as water vapor. Further heating promotes thermal decomposition of the fuel, which converts its volatile fraction to combustible gases/vapors and fixed carbon to combustible char. The oxygen in the air then combines with both the combustible gases/vapors and char to carry out the main combustion reactions. A large number of chemical reactions take place during the combustion process. However, the overall combustion chemistry can be illustrated by the following simple equations:

$$C + O_2 = CO_2$$

(oxygen in air combines with carbon in the fuel to form carbon dioxide)

$$2H_2 + O_2 = 2H_2O$$

(oxygen in air combines with hydrogen in the fuel to form water vapor)

Both of these chemical reactions are highly exothermic—they liberate large quantities of heat as the reaction proceeds. This heat is captured in a variety of equipment to provide energy for different end-use applications.

The most common equipment used for direct wood combustion and simultaneous heat exchange to produce useful energy is known as a boiler. This system uses water to absorb the heat energy released during the combustion of biomass fuels. Two methods of heat exchange are generally used in boilers: (a) fire tube, and (b) water tube. In the fire-tube design, hot combustion gases pass through the tubes and transfer the heat to the water surrounding them. In the water-tube design, water is put in the tubes and hot combustion gases transfer the heat from outside. Steam produced by either methods can be used to supply process heat and produce mechanical and electrical power for industrial and small utility applications (see Steam Turbines in Section B). These applications are discussed later in this section. The heart of a boiler system is the furnace, where the biomass fuel and air are brought in contact for actual combustion to take place. Also, the bulk of the heat exchange takes place in the furnace.

---

*Theoretical amount of air required to burn a combustible material.

**Weight of water divided by the total weight of "as-received" biomass.

Different furnace designs are available. Each design employs a distinct method of feeding the solid biomass fuel and bringing the air in the furnace. Boilers are generally grouped according to the furnace design. The common designs used for biomass combustion are:

- Dutch oven and fuel-cell furnace systems
- spreader-stoker furnace system
- suspension-burning systems

Within the above design categories, the grate system used for burning the solid fuel and removing the ash varies substantially.(1)* Fixed grates are generally used for small boilers. Larger boilers invariably use traveling grates, and the most common design is the "spreader-stoker" type. Each wood-fired or biomass-fired boiler design is based on the fuel characteristics and intended application. Within the design limitations, provisions can be made to burn different biomass fuels (wood residues, agricultural residues, etc.) either alone or in combination with conventional fuels like oil, gas, and coal.

Details regarding biomass-fired boilers, combustion chemistry, and calculations are presented in the state-of-art report.(2) However, quantitative data on biomass combustion process and equipment, as extracted from the selected literature sources, are given in Section C.

3. Current Status of the Technology.

Direct combustion of biomass, particularly woody biomass, to produce steam and electric power is widely practiced in the forest products industry (plywood, lumber, and pulp and paper) in the U.S. It is a well-known technology, and considerable operating experience has been accumulated through successful operation of wood-residue-burning installations in different forest products industries. For example, burning of wood waste (bark, low quality chips) and processing residue (black liquor) to supply part of the in-plant energy needs is an integral part of the present day-pulp and paper mill operations.

In the rural areas of developing countries, direct combustion of woody biomass (firewood) and agricultural waste has historically been used as a source of energy for cooking. Also, direct combustion of biomass is commonly used to supply steam and electric power in the forest products industry, sugar industry, and food industry.

As the price of conventional energy sources, and especially oil, rises, the utilization of processing waste to supply part of in-plant energy needs is becoming more popular among the different forest products industries. Consequently, many sawmill and plywood mill operators around the developing and developed world have either installed or are considering wood-waste boilers for producing steam and/or electricity. Also, four utilities in the U.S. produce electricity from wood.

Smaller systems using the fluidized-bed combustion technique are commercially available. These systems burn wet (moisture content greater than 50 percent*) and dirty (containing abrasive materials like glass) biomass fuels. Also, advanced fuel preparation techniques, i.e., densification or pelletization, are available to enhance the transportability and ease of handling of low-density biomass fuels. Combustion of pulverized biomass-derived char is being tested in boilers designed for pulverized-coal firing.

---

* Numbers in parentheses refer to numbered references listed at the end of this subsection.

* Weight of water divided by the total weight of the "as-received" fuel.

4. Technology Issues and Problems

Direct combustion of suitable biomass feedstocks is a proven technology, which has been in commercial application for quite some time. Major technical, environmental, economic, and social and institutional problems associated with this technology are highlighted in this section. For quantitative data and case-specific information on some of these factors see Section C. Detailed discussions of these factors are presented in the state-of-the-art report.(1)

o Technical. Boilers designed to burn different biomass feedstocks have been in commercial operation for a long time. Most of the technical problems associated with this technology are due to the variation and inconsistency of different biomass feedstocks. For example, the higher ash content of rice husks produces a low fusion temperature ash that can form slag on the boiler furnace and other heat transfer areas, and affect the boiler performance significantly. Also, cofiring of wood and coal promotes slagging. This is due to the incompatibility of wood and coal ash, which forms a low fusion temperature ash mixture. Special design considerations, such as the installation of extra soot blowers, can alleviate the ash-slagging problem.

Because of the lower heat content of biomass fuels as compared to fossil fuels, the combustion chambers of biomass-fired furnaces are larger than those of fossil fuel-fired furnaces of equal firing capacity (i.e. thermal output). The conversion of an existing fossil fuel-fired furnace to burn biomass fuel will therefore generally result in a reduction of furnace thermal output. Also, water-tube boilers burning biomass fuels use a larger tube spacing in the convective heat transfer area compared to their counterparts burning petroleum-derived fuels. Consequently, the major components of a biomass fuel boiler facility are bulky, making shop (or factory) assembly difficult for boilers producing more than 24,000 kg/hr (50,000 lb/hr) of steam. Fire-tube boilers produce steam on the shell side. Because of the larger diameters of the shell, these boilers are limited to low steam pressures, quality (dryness of steam), and capacities. Finally, direct combustion of pyrolytic char depends on its characteristics; char should contain proper volatile content for ease of ignition and flame stability. Low volatile content chars are difficult to ignite and exhibit very poor flame stability.

o Environmental. Emission of particulate matter can create air pollution problems for biomass combustion facilities. Several devices, such as cyclone separators, and wet and dry scrubbers, are available to reduce the particulate emissions. The sulfur content of biomass fuels is very low and sulfur oxides emission is not a problem for direct combustion. Also, because of the lower heating value and higher moisture content of biomass fuels, high combustion temperatures are not attained in the furnace, which, in turn, helps reduce the formation of undesirable oxides of nitrogen.

The leachates from fuel and ash piles can be a source of water pollution. The storage areas for these piles should be carefully designed to avoid any water run-off.

o Socioeconomic and Institutional. Even though direct combustion of biomass is an old and proven technology, its wide acceptance in developing countries can be constrained by certain social, economic, and institutional problems. The severity of these problems depends on a particular country situation, and some of these problems may be common to other biomass conversion technologies.

For example, the implementation of wood-fired (direct combustion) power plants to produce electricity in the rural areas of developing countries should be supplemented with an active forest resource management program to ensure the availability of biomass fuels. To accomplish this, institutional cooperation between local agencies managing forestry and electricity generation is required.

The high front-end capital requirement of direct biomass-fired power plants may discourage small grain and sawmill owners from using direct biomass combustion as an alternative to conventional petroleum-derived energy sources. Also, the competition for biomass feedstock for other nonfuel industrial applications may upset the economics of biomass fuel acquisition.

5. Future Development

Most of the research and development activities in direct combustion of biomass are focusing on fluidized-bed combustion. These systems will be capable of handling high moisture and dirty biomass fuels. Smaller fluidized-bed combustion systems are presently available in the U.S. for commercial applications. Also, combustion techniques are being developed that produce a higher rate of heat release by suspension burning of finely sized biomass feedstocks. These systems, when fully developed, can facilitate the retrofit of existing petroleum-derived fuel combustion equipment to burn solid biomass fuels.

6. Product(s) Utilization

Direct combustion of biomass releases the chemical energy of the fuel in the form of heat. In developed countries like the United States and European countries, forest product wastes are extensively used to provide process heat for the forest products and pulp and paper industries. In developing countries, biomass combustion has traditionally been used for cooking, conventional brick manufacturing, tea drying, charcoal making, etc. Also, on a limited scale, direct combustion of biomass is used to produce steam for industrial process heat and power application.

Details regarding the application of direct biomass combustion in developing countries are presented in the state-of-the-art report.(2) Some of those applications are briefly described here.

o For Cooking. Direct combustion of biomass and biomass-derived char has been used for cooking since the beginning of time. Even today, cooking over an open fire is widely practiced in the rural areas of many developing countries. This technique and traditional stoves are extremely inefficient and represent a poor utilization of biomass resources.

Simple improved stoves have been designed and tested in Guatemala, Indonesia, India, and Egypt.(3) These stoves are made from a mixture of clay and sand with some sheet metal and are reported in laboratory tests to cut firewood consumption approximately 50 percent in comparison with open fires.(2)

o For Steam/Power Production. Direct combustion of biomass and biomass-derived char can be used in boilers to produce steam. This steam, in turn, can be used to supply heat for a drying process or as process heat and to run a steam turbine to produce mechanical and/or electrical power. Generally, for supplying process heat, saturated low-pressure steam is used. However, high-pressure superheated steam is preferred for power applications. If both low-pressure steam and electrical power are required, a special steam turbine is used for this purpose (see Section B).

Solid biomass fuels and chars are completely different from petroleum-derived fuels. Therefore, existing petroleum-derived fuel combustion equipment cannot be easily modified for direct biomass combustion. In most cases, new combustion equipment will be required for direct firing of solid biomass fuels. One exception is the combustion of biomass-derived char as a char-oil slurry, which can be burned in existing equipment after proper modifications (see Char-Oil Slurry). Direct combustion of biomass, therefore, is considered to be an indirect substitute for conventional petroleum-derived fuels.

The forest products industry in the developing countries offers excellent opportunities for expanded use of direct biomass combustion technology. Some of the existing plywood mills already burn their own wood waste to produce steam for drying the lumber and finished products. However, many of the existing sawmills and plywood mills use diesel generators for supplying plant power requirements. The waste generated by these mills can be fired in boilers to produce steam/power for the mill operation. Also, where biomass resource is available, small biomass-fired (wood, rice husks, bagasse) electric power plants can be considered for electricity generation in remote and isolated rural areas.

References

1. "Boilers Fired with Wood and Bark Residues," D. C. Junge, Research Bulletin 17, Forest Research Laboratory, Oregon State University, Corvallis, Oregon. November 1975.

2. Direct Combustion to Produce Power from Biomass. A State of the Art Review. AID Office of Energy, Washington, D.C. (in preparation).

3. "Prospects for Traditional and Non-conventional Energy Sources in Developing Countries," World Bank Staff Working Paper No. 346, Washington, D.C. July 1979.

GASIFICATION
A Technology to Produce Low-Heat Value (Producer) Gas and Medium-Heat Value (Synthesis) Gas

1. Definition

Gasification of biomass is the thermal decomposition of the material in the presence of a limited (less than stoichiometric amount) supply of air to produce combustible fuel gases. When air is the only gasifying agent used in the process, the product gas mainly consists of carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen (N_2), with small amounts of hydrogen (H_2), methane (CH_4), and liquids. The quantity of hydrogen in the product gas can be increased by using steam along with air. Because of the nitrogen dilution, the product gas has low heating value* (less than 5,600 kJ/m^3 or 150 Btu/scf), and it is known as low-heat-value gas or producer gas. The nitrogen dilution of the product gas can be avoided by using pure oxygen instead of air as an oxidant. The gas produced by an oxygen-blown gasifier has medium-heating value (less than 13,055 kJ/m^3 or 350 Btu/scf) and it is known as medium heat-value gas or synthesis gas. Nitrogen can also be removed from a low-heat-value gas stream to enhance the heat value of the gas.

2. Technical Description

Low moisture (less than 40 percent**) bioresources like wood, and wood and crop residues are ideal feedstocks for gasification. For wood and many other types of biomass, the liquid fraction of the product gas consists of an insoluble viscous tar (phenolics) and a soluble fraction containing acetic acid, methanol, acetone, esters, aldehydes, and furfural. The latter are collectively known as pyroligneous acid. The quantity of these liquids depends on the type of biomass feedstock, operating conditions (i.e., temperature, residence time, etc.), and type of gasifier used.

The vessels (or reactors) used for converting biomass to gaseous fuel are called gasifiers. These gasifiers are usually characterized by the method of contacting solids (i.e., biomass) and reactant gases (i.e., air or oxygen and steam). The principal reactor configurations are:

— fixed-bed, updraft and downdraft

— fluidized-bed

— entrained-bed.

Many chemical reactions take place during a gasification process. For example, in the case of a fixed-bed updraft gasifier, three distinct reaction zones—drying, pyrolysis*, and combustion/gasification—can be identified. These reaction zones are presented for a fixed-bed updraft gasifier in Figure A-1. Representative generic reactions are outlined below:

Drying Zone: 100°-200°C (212°-392°F)

moist wood + heat $\longrightarrow$ dry wood + water vapor

Pyrolysis Zone: 200°-500°C (392°-932°F)

dry wood + heat $\longrightarrow$ char + CO + CO_2 + H_2O + CH_4 + other hydrocarbons + pyroligneous acids + tars

Gasification and Oxidation Zone

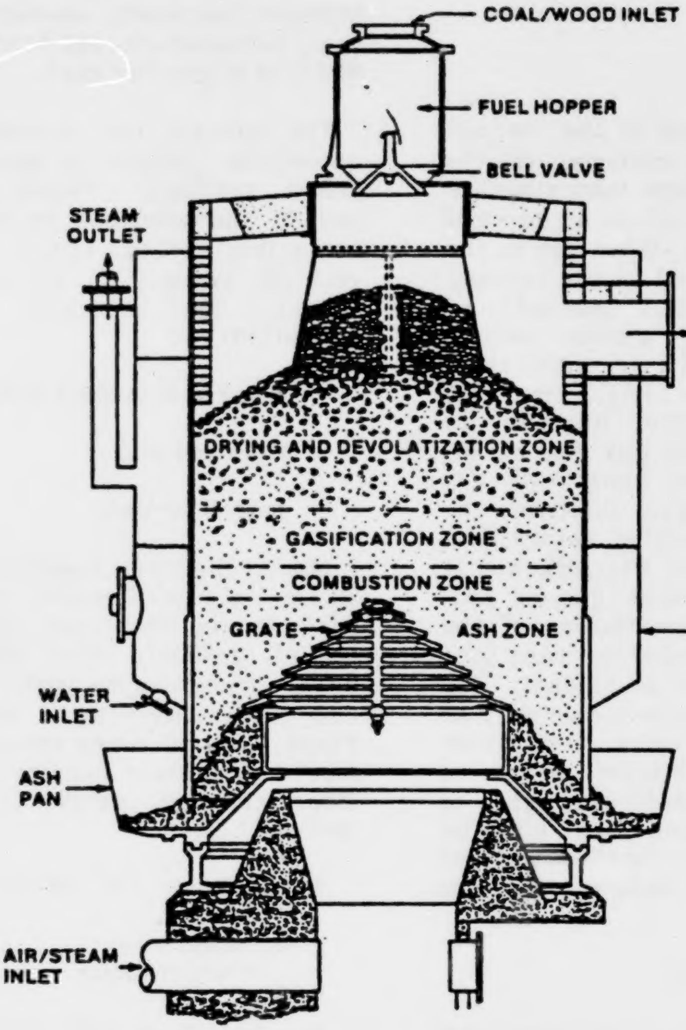
char + O_2 + H_2O $\xrightarrow{\text{steam}}$ CO + H_2 + CO_2 + heat

---

*Heating value here refers to the gross amount of heat liberated when a specific quantity of fuel gas is burned with oxygen.

**Weight of the water divided by total weight of "as-received" biomass.

* Pyrolysis is the thermal degradation of carbonaceous material in the absence of reacting gases (i.e., oxygen or air).


COAL/WOOD INLET
FUEL HOPPER
BELL VALVE
STEAM OUTLET
GAS OUTLET
DRYING AND DEVOLATIZATION ZONE
GASIFICATION ZONE
COMBUSTION ZONE
GRATE
ASH ZONE
STEAM JACKET
WATER INLET
ASH PAN
AIR/STEAM INLET

Source: "Wood Gasification: An Old Technology with New Potential for the Eighties," J. J. Fritz, A. Talib, and J. J. Gordon, presented at the 178th Meeting of the American Chemical Society, Washington, DC, September 1979.

FIGURE A-1
SINGLE-STAGE FIXED-BED WOOD GASIFIER

In general, during gasification of biomass feedstock, volatile matter undergoes pyrolysis reactions producing products like carbon monoxide, carbon dioxide, water vapor, hydrogen, methane, and small quantities of higher hydrocarbon gases, liquids, and char. The char (mostly carbon) then reacts with air or oxygen and steam, if used as a reactant, to produce additional CO, CO_2, and H_2. The reaction between steam and carbon requires significant quantities of heat energy. This energy is supplied by the heat released by the combustion of char.

Details regarding different gasifiers, gasification chemistry, and product gas yield composition and quality can be found in the state-of-the-art reports on gasification technology.(1,2)* However, quantitative data on gasification technology, as extracted from the selected literature sources, are presented in Section C of this handbook.

3. Current Status of the Technology

Of the different types of gasifiers mentioned earlier, air-blown fixed-bed (both up- and downdraft) gasifiers have been used commercially to convert wood/biomass into a fuel gas. The capacities of these gasifiers range from small to intermediate (5 kg of biomass per hour to 10 tons per hour). The gas produced from these gasifiers was used for many years in different parts of the world in internal combustion engines (both stationary and mobile), steam boilers, ceramic kilns, etc. Because of the availability of cheap petroleum fuels, the popularity of these gas generators was lost, and by 1950 this technology was more or less abandoned. However, as the availability of petroleum-derived fuels is shrinking, the old air-blown biomass/wood gasification technology is now being revitalized.

In North America and in Europe, several firms are ready to supply air-blown wood/biomass gasification systems. A list of these firms and description of their gasification systems are given in the state-of-the-art reports.(1,2) Some of these firms have enough commercial experience with their gasifiers to consider them proven technology. Others have gasifiers commercially available but have limited operating experience with their units. These gasifiers are available for supplying fuel gas to internal combustion engines and small industrial boilers.

Advanced biomass gasification techniques like high-pressure oxygen-blown gasification, catalytic gasification, and fluidized-bed gasification are being developed at several research centers in the U.S and elsewhere. These gasification technologies are particularly being developed for large-scale synthesis gas, an appropriate mixture of carbon monoxide and hydrogen, production operations. Currently, bench-scale experiments and, in some cases, pilot-scale testing are being conducted to determine optimum operating parameters for these advanced biomass gasification processes. If the ongoing technology development activities are carried through, large-scale demonstration plants could be started in the U.S. by 1990. The product synthesis gas from these advanced gasifiers can be used for the production of methanol and other fuels and chemicals. It can be directly used as a medium-heat-value fuel gas for industrial boilers, kilns, gas turbines, and other direct combustion applications. Specific applications of the product gases from different gasifiers are discussed in a later section.

4. Technology Issues and Problems

Air-blown biomass gasifiers have been successfully used in some developing countries. Some of these gasifiers are still in operation in west Africa, the Phillipines, and Central America.(1) Potential technical, environmental, economic, and social and institutional problems associated with this technology follow. For quantitative data and case-specific information on these factors see Section C. A detailed discussion of these factors is presented in the state-of-the-art reports.(1,2)

---

* Numbers in parentheses refer to numbered references listed at the end of this subsection.

o Technical. Fixed-bed (both up- and downdraft) air-blown biomass gasification systems are fairly simple and reliable off-the-shelf equipment.(1) Most of the operating difficulties associated with fixed-bed gasifiers are caused by inconsistency of the biomass feedstock used. Uniform particle size and lower moisture content are important for trouble-free operation of these gasifiers. This is particularly important in the case of downdraft gasifiers, where the presence of fine particles in the feedstock can cause plugging and bridging of the gasifier, and the presence of high moisture promotes the formation of tar. The updraft gasifier produces large quantities of tar and its condensation causes many operating difficulties.

The difficulty of feeding biomass feedstock at high pressures is one of the main concerns in the development of advanced high-pressure gasification systems. Biomass feedstocks tend to bridge at high pressures which hinders the normal flow of the material. Drying and fine grinding of biomass are expensive and high energy-consuming operations. Therefore, any gasification process requiring finely sized feed material will not be suitable for gasifying biomass feedstock. Finally, advanced gasification processes, when developed, will use more complex technologies and their suitability for application in developing countries should be evaluated on a country-by-country basis.

The availability and proximity of biomass feed materials are very important for the successful implementation of a biomass gasification project. The dispersed nature of the biomass feed materials is more conducive to small- and medium-scale biomass gasification projects. For large-scale gasification projects, the availability and transportability of biomass feed materials should be carefully evaluated.

o Environmental. The major environmental problem of biomass gasification technology is the disposal of organic liquids produced during the gasification process. This is particularly true for fixed-bed updraft gasifiers in which larger quantities of organic liquids are produced. The amount of organic liquids produced, to a certain degree, can be reduced by using low moisture feedstocks. Also, certain design modifications, i.e., recycle of hot product gas, can reduce the quantity of organic liquids in the final product gas. However, use of other types of gasifiers (i.e., downdraft, entrained-bed, fluidized-bed) is recommended for effective elimination and/or reduction of organic liquids production. Details regarding different types of gasifiers are presented in the state-of-the-art reports.(1,2) Relevant quantitative data on the environmental factors of gasification technology are presented in Section C.

o Socioeconomic and Institutional. Even though small air-blown biomass gasification systems are a fairly simple and reliable means of supplying energy in different sectors of developing countries (see section on product utilization), their wide acceptance can be constrained by social, economic, and institutional problems which depend on particular country situations. However, some of these problems may be common to other biomass conversion technologies.

For example, small landholders, small grain and sawmill owners may not have the capital to purchase biomass gasification systems (small power generators). Also the use of these systems by rich farmers and mill owners might deprive the poorer section of the rural areas from otherwise free or low-cost fuel (crop residue, mill waste, etc.).

The availability and cost of capital might constrain the implementation of biomass gasification projects. In addition, the economic attractiveness of large and complex advanced gasification technologies to a large extent will depend on the manufacturing capability of a particular developing country.

5. Future Development

As mentioned earlier, most of the research and development work in the biomass gasification area focuses on the development of high pressure oxygen-blown gasifiers. Catalytic gasification and dual fluid-bed gasification systems are being developed at research centers in the U.S. For a detailed description of advanced gasification systems, see the state-of-the-art report.(1)

6. Product(s) Utilization

The product of air-blown biomass gasification is a fuel gas which contains carbon monoxide and hydrogen as the principal combustible fractions. Because of the presence of large quantities of nitrogen and carbon dioxide, the gas has a low-heat-value (i.e., energy content) and is known as low heat-value gas or producer gas. When oxygen, instead of air, is used in the gasifier, the product gas is free of nitrogen. It essentially consists of a mixture of carbon monoxide and hydrogen and it is known as medium-heat-value gas (or synthesis gas; the term synthesis gas is usually reserved to a mixture of H_2 and CO in the proportions desired for carrying various chemical synthesis reactions).

The exact composition of these gases is a function of the feedstock and the operating conditions. Details regarding the composition and heating value of the gas for different feedstocks and operating conditions are presented in the state-of-the-art report.(1) Also, some of these data are presented in Section C.

The products of biomass gasification, both low- and medium-heat-value gases, can be used as direct fuels in different energy consuming sectors of developing countries. Low-heat-value gas can be used as a supplement fuel for industrial boilers, internal combustion engines and to provide mechanical and electrical power to small industries and agriculture (mills, irrigation, etc.). The medium heat-value gas (or synthesis gas) can be used as a precursor for liquid fuels and chemicals. The production of medium-heat-value gas, however, requires high capital and engineering costs; its attractiveness for applications in developing countries is, therefore, more limited than that of low-heat-value systems.

o As a Fuel for Steam/Power Production. The low-heat-value gas produced from air-blown gasifiers can be used as a fuel for close-coupled* new and existing oil- and gas-fired boilers. Packaged (shop assembled) oil- and gas-fired boilers, producing up to 68,000 kg/hr (150,000 lb/hr) of steam, are suitable for this application. Only large-size air-blown gasifiers can provide a good match for these package boilers. New boilers, designed specifically for low-heat-value gas, can operate on the low-heat-value gas without any operational difficulties. However, the use of low-heat-value gas in existing package oil- and gas-fired boilers requires some modifications. The extent of these modifications depends on the original design of the boiler to be retrofitted and the quality (particularly heating value) of the low-heat-value gas in comparison with the original fuel (i.e., natural gas, distillate oil, and residual oil). In general, the modifications that may be necessary when retrofitting existing oil-/gas-fired boilers to burn low heat-value gas include:

- installation of new burners and control system
- installation of a new fuel supply system
- uprating, or replacement, of forced and induced draft fans.

---

* Because of the lower heating value, the product gas cannot be economically transported over long distances.

The use of low-heat-value gas in existing oil-/gas-fired boilers, in most cases, will introduce some derating in the original capacity of the boiler. The magnitude of this derating will depend on the heat value (energy content) of the biomass-based fuel gas.

Medium-heat-value gas can also be burned in new and existing oil- and gas-fired boilers. Once again new boilers, when specifically designed to burn this gas, will run on medium-heat-value gas without any difficulty. Also, the use of medium-heat-value gas in the existing oil- and gas-fired boilers will involve fewer modifications as compared with the use of low heat-value gas. However, the higher cost of medium-heat-value gas will prevent its use as a boiler fuel for close-coupled applications. If the fuel gas needs to be transported over a reasonable distance (more than 160 km or 100 miles), then the medium-heat-value gas will give a lower overall delivered cost at the point of use.

The steam produced in the package boilers can be used to supply process heat and power. This type of boiler is commonly found in industry and is also used in some utility operations. Higher pressure steam is required for power applications. These boilers are capable of delivering medium- to high-pressure steam with a reasonable degree of superheat. This high-pressure steam, when passed through a steam turbine, can produce mechanical or electrical power. For information on steam turbines see Section B.

o As a Fuel for Direct Oil- and Gas-fired Equipment. Low-heat-value and medium-heat-value gas can be used in some direct oil- and gas-fired industrial equipment. Typical examples of this equipment are: lumber kilns, veneer dryers, pulp dryers, paint dryers, lime and brick kilns, and cement kilns.(1) The modifications necessary to retrofit existing oil- and gas-fired equipment depend on the type of equipment under consideration and the quality of low-heat-value gas. In general, they will be similar to those required for retrofitting boilers. However, if some of these direct-fired applications require higher flame temperatures (i.e., cement and lime kiln operations), then substitution of low-heat-value gas for oil and gas might be impractical. In these situations, use of medium-heat-value gas should be explored.

o As a Fuel for Internal Combustion Engines. Low-heat-value gas can be used in both mobile and stationary internal combustion engines. The two most common internal combustion engines are the Otto cycle (spark ignition) engine used in automobiles and the diesel (compression ignition) engine used in buses, trucks, and automobiles.

Stationary engines of both types, particularly diesel type, are generally used in the developing countries to power irrigation pumps, to run electric generators for power generation in rural areas, and to run grain and sawmills.

These engines, after necessary modifications, can run on low-heat-value gas produced from biomass gasification. The Otto engine requires minor modifications, i.e., replacement of carburetor with mixing chamber for burning low-heat-value gas. Whereas conversion of existing diesel engines to burn 100 percent low heat-value gas is difficult, a more practical approach is to convert the diesel engine to a dual-fuel mode. In this mode, about 5 to 10 percent diesel fuel is used with the low-heat-value gas to provide the ignition at higher pressures. This small amount of diesel fuel is normally supplied by the existing fuel pump and injection system. For a detailed description see Section B.

Small- to intermediate-size gasifiers are suitable for supplying fuel to different internal combustion engines. Large-size gasifiers may be required when converting large capacity, slow speed, stationary engines. These large engines are typically used for electricity generation in the rural areas of developing countries. The use of low-heat-value gas in the existing internal combustion engines will introduce some engine derating. However, since most of the engines are oversized, this derating may not affect their normal power output. For quantitative data on the use of low-heat-value gas in internal combustion engines, see gasification subsections in Section C.

o As a Fuel for Gas Turbines. Gas turbines burn natural gas and lighter liquid fuels to provide mechanical power (shaft work). If electricity is the desired product, then a generator can be hooked to the turbine (see Section B for more details). Low- and medium-heat- value gases can be used in the existing gas turbines by suitable modifications to the turbine control system, gas-fuel components, and fuel handling system. The extent of these modifications will be relatively easier for medium-heat-value gas as compared with low-heat-value gas. In most cases, the retrofit of existing turbines to burn low-heat-value gas will be impractical. Also, where retrofit of existing turbines is possible, the fuel gases should be very clean to avoid any turbine blade damage and assure a trouble-free operation. Heat exchanges to heat air for use in the turbine may be necessary.

Gas turbines are generally larger in size (i.e., power rating) than internal combustion engines. Therefore, only large capacity gasifiers are suitable for supplying their fuel needs. Also, the use of gas turbines in developing countries is not as common as internal combustion engines. They may be found in some industrial and utility operations.

Future advances in gas turbine technology will improve the fuel flexibility (see Section B), and the adoption of low- and medium-heat-value gases will become simple. Also, advanced high pressure biomass gasification systems will be more compatible with gas turbine technology than the state-of-the-art atmospheric pressure gasifiers.

o As a Feedstock for Methanol and Other Liquid Fuels. Methanol and other liquid fuels can be synthesized from the medium-heat-value gas by using different intermediate conversion technologies (see Section B).

If the medium-heat-value gas (or synthesis gas) is to be used for methanol and other liquid fuels syntheses, proper conditioning of this gas is required before synthesis. Depending on the type of liquid fuel desired, a certain molar ratio of hydrogen to carbon monoxide should be present in the synthesis gas. The synthesis gas should also be free from gases such as carbon dioxide, hydrogen sulfide (H_2S), and methane.

Oxygen-blown biomass gasifiers, preferably operating at high pressures, can be used for producing medium-heat-value gas; only large capacity gasifiers are suitable for integrating with methanol and other liquid fuel production schemes. Historically, most plants for the conversion of synthesis gas to liquid fuels have used the Fischer-Tropsch synthesis (see Section B); in the presence of a special catalyst, the synthesis gas is converted into a variety of gaseous and liquid hydro- carbon fuels. These liquid hydrocarbon fuels are upgraded, using conventional petroleum technology so that they can be substituted for conventional petroleum-derived liquid fuels. Methanol, however, cannot be directly substituted for conventional liquid fuels in the existing internal combustion engines. Blends of methanol and gasoline are successfully burned in automobile engines (see Section B). The use of methanol in gas turbines and industrial boilers is still being tested. One potential use of methanol is its direct coversion to gasoline, using Mobil M-gasoline process. This process is near its commercial application (see Section B).

References

1. Gasification: Small and Large Systems and their Use. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

PYROLYSIS
A Technology to Produce Char, Pyrolytic Oil and Gas

1. Definition

Pyrolysis is the thermal decomposition of solid carbonaceous fuels in the absence of air. This process produces combustible gases, oils, and solid char. When air is not present in the system, the heat input for pyrolysis is provided by burning a conventional fuel or part of the product gases. Most of the pyrolysis processes, however, use a small quantity of air, and the partial combustion of a portion of product char supplies the pyrolysis heat.

2. Technical Description

The major differences between gasification and pyrolysis are the operating temperatures and quantity of air (when partial oxidation is used to supply the process heat) used in the process. The gasification process uses more air than the pyrolysis process and, consequently, higher temperatures are reached during gasification.

Low-moisture (less than 30 percent*) bioresources like wood, wood residue, and crop residue are ideal feedstocks for pyrolysis. In general, the relative yields of the pyrolysis products depend on the nature of the feedstock.

In addition, the operating temperatures and the presence of water vapor in the low temperature pyrolysis system control the relative yields of gas, oil, and char products. Higher temperatures favor the production of gas and decrease the char and oil yields. The presence of water vapor in the system promotes the formation of richer gas when appropriate operating conditions are achieved in the gasifier.

Most of the major chemical reactions which take place during gasification (see Gasification) are common to the pyrolysis process, except for the steam-char reaction. In addition, in an indirectly heated pyrolysis system, the absence of air eliminates char combustion reactions and produces a gas of higher heat-value. Typical reaction zones of an indirectly heated pyrolysis process are presented in Figure A-2. Representative generic reactions follow.

Drying Zone: 100°-200°C (212°-392°F)

moist wood* + heat

yields:

dry wood + water vapor

Pyrolysis Zone: 200°-500°C (392°-932°F)

dry wood + heat

yields:

char + CO + CO_2 + H_2O + CH_4 + H_2

+ other hydrocarbons

+ pyroligneous acids

+ tars

In general, during pyrolysis of biomass, the volatile fraction of the feedstock undergoes thermal decomposition producing products like carbon monoxide (CO), carbon dioxide (CO_2), water vapor, hydrogen (H_2), methane (CH_4), other higher hydrocarbon gases and condensable vapor of pyroligneous acid**, tars***, and solid char. The presence of water vapors in the producer gases, depending on the operating conditions (i.e., temp-

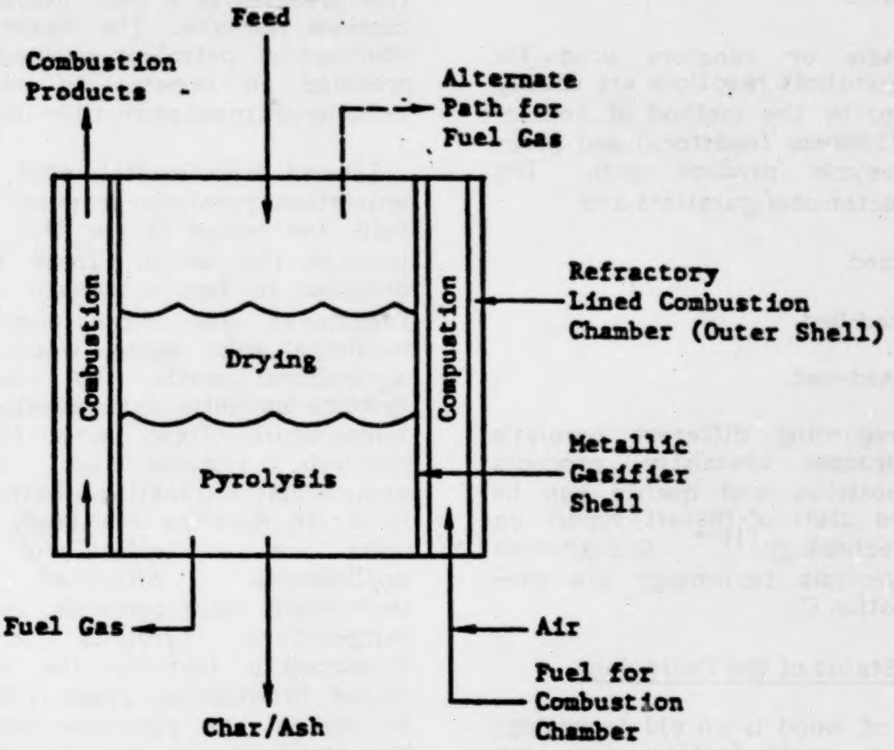
---

*Weight of water divided by total weight of "as-received" biomass.

*Or any low-moisture biomass feedstock.

**Contains water-soluble organic compounds such as acetic acid, methanol, etc.

***Contains water-insoluble viscous phenolics.


Biomass
Feed
Combustion
Products
Alternate
Path for
Fuel Gas
Refractory
Lined Combustion
Chamber (Outer Shell)
Combustion
Drying
Combustion
Metallic
Gasifier
Shell
Pyrolysis
Fuel Gas
Air
Fuel for
Combustion
Chamber
Char/Ash

Source: State-of-the-Art Review: Pyrolysis of Wood and Agricultural Biomass, Anil K. Chatterjee. USDA/FS and AID, Washington, DC. 1981.

FIGURE A-2
REACTION ZONES OF AN INDIRECTLY HEATED PYROLYSIS PROCESS

erature pressure, etc.), may promote gas phase steam reforming* of the higher hydrocarbons and tars, producing additional gases. The resulting pyrolytic oil is essentially composed of the condensed tars.

The vessels or reactors used for conducting pyrolysis reactions are usually characterized by the method of contacting solids (biomass feedstock) and gases (air or recycle product gas). The principal reactor configurations are:

- fixed-bed
- fluidized-bed
- entrained-bed.

Details regarding different pyrolysis reactors, process chemistry, products yield, composition, and quality can be found in the state-of-the-art report on pyrolysis technology.(1)** Quantitative data on pyrolysis technology are presented in Section C.

3. Current Status of the Technology

Pyrolysis of wood is an old technology utilized in a crude fashion since the beginning of time. Pyrolysis of wood was used in the U.S. and other countries before, during, and after World War I to produce char, tar, pyroligneous acid, and gases. Nowadays, charcoal has become the primary product of pyrolysis in the U.S.; with the development of synthetic chemicals, the use of pyrolysis fuel gas as chemical feedstock has ceased in the U.S. The use of this technology in a crude fashion, however, is still being practiced in several developing countries. Brazil is one of the countries where wood is pyrolyzed in beehive-type kilns to produce charcoal for the pig iron industry. These charcoal producers are not designed to collect and use the gaseous and liquid by-products produced during the pyrolysis of wood. Therefore, in terms of energy efficiency, this practice is a poor utilization of a biomass resource. The recent worldwide shortage of petroleum-derived fuels has provided an impetus to improve the existing charcoal production technologies.

Several experimental, pilot, and demonstration pyrolysis systems have been built and tested in the U.S. and other parts of the world. These units were designed to test a variety of biomass feedstocks, the most common being municipal solid waste, wood chips, and agricultural waste. Of the pyrolysis systems currently under development, low temperature fixed and fluidized-bed pyrolysis systems are ready for commercial application. Several vendors in North America are ready to deliver units for a variety of industrial applications. Advanced pyrolysis technology, flash pyrolysis, or fast high temperature pyrolysis are being developed to increase the amount of higher hydrocarbon gases (ethylene) and liquids in the pyrolysis product mix. These technologies are in their early stage of development, and a considerable amount of pilot-scale work is required before their commercial viability can be evaluated. Flash pyrolysis of biomass would require extensive front-end preparation procedures.

4. Technology Issues and Problems

The commercial application of continuous and improved pyrolysis technologies has not yet been tried in developing countries. Potential technical, environmental, economic, and social and institutional problems associated with this technology follow. For quantitative data and case-specific information on these factors, see Section C. Detailed discussion of these factors is presented in the state-of-the-art report.(1)

o Technical. Most of the technical problems listed for biomass gasification technology (see Gasification) are also common to pyrolysis. Since the yield and quality of pyrolysis products (char, oil, and gas) depends on the consistency (i.e., particle size, moisture content, etc.) of biomass feedstock and operating conditions like process temperature and residence time, careful control of these factors is extremely essential to produce a consistent quality product. Recovery of pyrolysis products is another area where proper attention should be given. The separation of tar and other condensable organic vapors from product gas can cause various operating troubles. The product char from the new continuous pyrolysis schemes, in most cases, is in powdered form. The powdered charcoal needs to be briquetted for ease of handling and transportation. The product oil is a highly oxygenated viscous liquid, with mild corrosive properties. Special care should be taken in long-term storage of this material. Also, the low-heat- value product gases, except for on-site use, cannot be economically transported over a long distance for other uses.

---

*The breaking of larger hydrocarbon molecules into smaller molecules.

**Numbers in parentheses refer to numbered references listed at the end of this subsection.

Since pyrolysis produces three different energy products, its viability depends on the availability of markets for these energy products. Also, where markets are available, only relatively large-scale plants (100 tonnes or 110 tons of dry biomass per day) will be capable of marketing the oil and char effectively. For large-scale projects, however, the availability and transportability of biomass feed materials should be carefully evaluated. On-site pyrolysis reactors can, however, supply fuel energy to small-scale industry like rice mills.

o Environmental. The major environmental problem of biomass pyrolysis technology is the disposal of water-soluble organic liquids produced during the pyrolysis process. This water disposal problem is aggravated when direct water cooling is employed to condense the product oil. The use of a specially designed air-cooled condenser may alleviate this problem to a certain degree and provides an alternate cooling scheme for water-scarce areas.

As indicated earlier, the pyrolysis plants will require large quantities of biomass feedstocks. Only large forest resources can satisfy their feedstock demand. However, active forest management and reforestation programs should be implemented before wide-scale use of pyrolysis technology to avoid possible deforestation.

o Socioeconomic and Institutional. A large number of developing countries are currently using beehive kilns to supply charcoal needs of both residential and industrial sectors. These technologies, even though highly energy inefficient, are very labor intensive and provide jobs for many people. The introduction of highly automated continuous pyrolysis technologies may increase the unemployment problem in many developing countries. Also, the equipment and most of the components of these continuous systems may have to be imported and their high capital cost will cause a drain on the foreign exchange. The availability of spare parts may also affect the operation of these plants. These factors should be carefully evaluated before any decision to implement this technology is taken. Simpler versions of the continuous pyrolysis plants should be preferred over the highly automated systems.

5. Future Development

The high temperature and lower residence time used in flash pyrolysis processes promote the formation of liquid products and higher hydrocarbon gases at the expense of reduced char yields. These processes are primarily developed to produce synthetic liquid fuels from municipal solid waste and other biomass feedstocks.

If charcoal is the desired product, several promising techniques are being developed using chemical pretreatment of fuel to enhance char production. Many salts promote char formation by initiating pyrolysis at lower temperatures to prevent or reduce the gas and liquid formation.

A wet high-pressure pyrolysis (or carbonization) process is also being developed to convert biomass material into char. This process uses an extruder to feed the biomass feed slurry into the reactor heat zone where pyrolysis of the feed takes place at high pressure and temperature in the presence of water. The by-product fuel gas produced during the process is sufficient to supply the heat requirements of the process. For a detailed description on advanced pyrolysis systems, see the state-of-the-art report.(1)

6. Product(s) Utilization

Pyrolytic gas has low to intermediate energy content. A low-heat-value gas cannot be economically transported over long distances. The best use of this product would be at the plant site. It could be, for example, used to supply the pyrolysis heat and in-plant power to run the equipment.

Product char is a high-energy-density, low-sulfur-content solid fuel. Its physical and chemical properties depend on the type of biomass feedstock and the operating conditions of the pyrolysis reactor. It is currently being used as a fuel in both residential and industrial sectors of many developing countries.

Pyrolytic oil is a highly oxygenated viscous liquid with slightly corrosive properties. The oil is not similar to any conventional petroleum-derived liquid fuels. However, with proper equipment modifications, it can be burned in industrial and utility (electricity generation) heavy-fuel-oil-burning installations. Some potential uses of pyrolytic oil and char follow. Extraction of chemicals from pyrolytic oil should be investigated. Details regarding the yield and characteristics of pyrolysis products for different biomass feedstocks and operating conditions are presented in the state-of-the-art report.(1) Also, some of these data are presented in Section C.

o Char as a Fuel for Cooking/Heating. Charcoal is used as a cooking and heating fuel in the rural areas of several developing countries. Earth pits and beehive kilns for charcoal production and for open-hearth stoves charcoal utilization are extremely inefficient. The use of charcoal in appropriately designed cooking stoves will eliminate the inefficiencies associated with the current charcoal utilization practices. The operating conditions of the pyrolysis reactor should be carefully controlled to obtain a char product containing reasonable volatile content so that it can be easily burned in domestic cooking stoves. If the product char is in powdered form, it may be combined with starch or another binding agent to form briquets which can be easily handled and transported.

o Char as a Fuel for Steam/Power Production. The char produced by the pyrolysis of biomass, depending on its volatile content, can be burned in boilers designed to burn pulverized coal. If the volatile content of the char is low, an auxiliary fuel such as natural gas or fuel oil may be required for flame stabilization. Another emerging application is to use char in existing residual or heavy-oil-fired industrial and utility boilers as a char-oil mixture. The feasibility of this application, however, depends on the successful adoption of coal-oil mixture combustion technology for the char-oil mixture combustion. Preliminary tests of burning char-oil mixture in a small residual oil-fired boiler have been encouraging and the retrofit of existing residual oil-fired boilers to burn a char-oil mixture seems technically feasible (see Char-Oil Slurry Combustion section and state-of-the-art report).

The use of char-oil mixture in boilers would save substantial quantities of petroleum-derived fuels (residual oil) in both industrial and utility sectors of developing countries (see Char-Oil Slurry Combustion).

o Char as Direct-fired Industrial Fuel. Charcoal has been used in the U.S. and other countries to dry hops, tobacco, and similar commodities.(1) High volatile content charcoal has many industrial applications. Pulverized char can be used in several calcination operations. For example, pulverized char can be used to fire lime and brick kilns and charcoal has been used in the manufacture of portland cement.

o Char as a Metal Reductant. Many countries such as Brazil, Malaysia, India, Argentina, the U.S., and several in Europe, use charcoal, produced by conventional methods, in the reduction of iron ore to produce pig iron. The charcoal-based smelting industries are backed by a large, well-managed forestry resource. The charcoal used in the smelting process requires high strength and density. Use of hardwood and proper operating conditions (i.e., feedstock, particle size, temperature and residence time) in the pyrolysis process, will ensure the production of suitable quality char. In general, unless briquetted, powdered char may not be suitable for supplying fuel/reductant to the iron smelting industry.

o Pyrolytic Oil as Fuel for Steam/Power Production. These oils are heavily oxygenated and are more viscous than petroleum-derived liquid fuels. Because of the presence of large quantities of phenolic and carboxylic substances, they tend to be acidic, corrosive, and unstable. Combustion and stability tests should be conducted to confirm the suitability of substituting pyrolytic oil for residual oil in most boiler installations. Pyrolytic oil is preferably to be used in cofiring with residual fuel oil.

In short term (one to two hours) combustion tests of pyrolytic oil showed satisfactory combustion characteristics (flame temperature, flame length, etc.). Based on the results of these tests, the following general conclusions on the utility of pyrolytic oil can be drawn:(2)

—In general, the pyrolytic oils performed satisfactorily. It must be stressed that the pyrolytic oil is not interchangable with distillate or residual oils in most boiler installations without modifications to storage and pumping facilities. This is a result of several unique properties of the pyrolytic oils: they are acidic, which requires additional consideration in shipping, storage, pumping, and piping; their properties change if the oils are allowed to evaporate at firing temperature for appreciable lengths of time; and they can form deposits on valves and heating surfaces if the pumping system is not properly designed.

—Pyrolytic oils appeared to be compatible with most residual fuel oils from different geographical sources. However, it was found that the residual oils did not completely purge the fuel system of pyrolytic oils. In order to avoid decomposition problems, the pyrolytic oil can only be blended with No. 6 oil and heated just before the burner nozzle and not in the oil storage tanks.

—The most likely initial problems encountered by pyrolytic oil users would be in quality control, storage, pumping, and atomizer blockage. Users should run thorough pumping and atomizing tests before attempting to fire these oils.

—The pyrolytic oils tested had such low sulfur content that no problems due to sulfur oxide corrosion or sulfur oxide emissions are anticipated from this oil.

—A lower heat content for pyrolytic oil (25 to 30 percent less than that of a similar volume of residual oil) requires greater fuel pumping and storage capacity for a given heat release rate.(2)

References

1. Pyrolysis: Charcoal and Pyrolytic Oils and their Use. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

2. Technical and Economic Assessment of the Mobil Pyrolysis Concept, Marvin Drabkin, MTR-79W438, The MITRE Corporation, McLean, Virginia, U.S. December 1979.

CHAR-OIL SLURRY COMBUSTION
A Technology to Produce Heat and/or Steam

1. Definition

Char here refers to solid carbonaceous fuel produced by the pyrolysis of biomass feedstocks (see Pyrolysis). The combustion of a mixture of this char and heavy fuel oil is referred to as biomass char-oil slurry combustion (BCOM).

2. Technical Description

Char-oil slurry combustion technology is analogous to coal-oil slurry combustion, which is also known as coal-oil mixture (COM) technology. The coal-oil mixture technology has been developed to substitute powdered coal for a portion of the fuel oil (heavy or residual oil) in industrial and utility (electricity generation) combustors capable of firing a coal-oil mixture. The biomass char-oil slurry or biomass char-oil mixture (BCOM) combustion described here is intended to be used for a similar substitution of powdered char. The description of BCOM combustion, for the most part, follows the COM combustion process. However, some special considerations necessary because of the differences in coal and biomass- derived char properties are also mentioned.

Low-moisture (less than 30 percent) bioresources like wood, wood residue, and crop residue are ideal feedstocks for the production of char. The quality and quantity of char produced by pyrolysis depends on the feedstock type and operating conditions of the process. Char for use in BCOM combustion should have a low-ash content. Combustion of a low-ash slurry will decrease ash deposits on heat transfer surfaces and on the furnace bottom, thus reducing the metal erosion caused by the inorganic constituents of ash. The details regarding the BCOM combustion are presented in the state-of-the-art report.(1)* A brief description of steps in the BCOM combustion are given below. Because very few experiments have been performed on BCOM, many of the factors associated with its combustion have to be explained in terms of the COM combustion.

The first step in the BCOM combustion process is the preparation of a pumpable char-oil slurry. This step can be performed either on site or in a remote central preparation and distribution facility. The COM (coal-oil mixture) or coal-oil slurry is prepared by pulverizing the coal to a desired particle size and mixing it with the heavy fuel oil (residual oil) and a stabilizing additive in a blending tank equipped with an agitator. A similar preparation scheme can be adopted for BCOM preparation. However, it should be noted that charcoal or biomass-derived char has significantly different physical properties than coal. The grinding procedures for charcoal will have to be appropriately modified. Alternative slurry preparation techniques are given in the state-of-the-art report.(1)

During storage, the BCOM is kept under mechanical agitation to avoid any settling of pulverized char. The fuel pumps and the transfer pipes should have erosion-resistant linings. Once again the recent experience gained in handling COM can be used for effective handling of BCOM.(1) The final step in the combustion of BCOM is its actual firing. For the COM combustion, modified standard heavy oil (residual oil) burners have been used for this purpose. The extent of the modifications depends on the type of burner originally installed. Various types of steam and air-atomized burners have been tested for COM combustion in different boilers. It has been found that the burner train components and burner nozzles should be made of erosion-resistant materials. After these modifications the COM burns similarly to residual or heavy oil. Similar results can be expected from the combustion of BCOM in existing residual-oil-fired equipment.

---

* Numbers in parentheses refer to numbered references listed at the end of this subsection.

3. Current Status of the Technology

The COM combustion technology is ready for commercial application. Several commercial-scale demonstration projects are currently underway in the U.S. The potential technical risk of conversion to COM has been reduced, and there are signs that the private industrial sector in the U.S. is beginning to regard COM as a viable alternate fuel. Residual-oil-fired boilers in several large utilities were retrofitted to burn COM and they have operated without any major difficulties. In fact, some of these units have accumulated several hundred hours of successful continuous operating experience. In short, the COM preparation and combustion technology is ready for commercial application in the U.S., and some private industrial sector activity is already moving in this direction.

Unlike COM, very limited tests have been conducted in the preparation and actual combustion of BCOM. The combustion of BCOM in a small residual-oil-fired boiler has produced some encouraging results (see Section C). Excellent flame stability was achieved and carbon combustion efficiency, similar to residual fuel oil, was obtained. More research and development work is required in the area of BCOM preparation, handling, and combustion before the technology can be considered ready for commercial application. However, the recent advances made in the COM area will facilitate the rapid development of BCOM for commercial applications.

4. Technology Issues and Problems

The COM combustion technology has reached an advanced stage of development. Most of the technology-related issues and problems have been addressed. These issues and problems are also common to BCOM technology. A description of the major technical, environmental, economic, social, and institutional problems of this technology follows. For quantitative data and case-specific information on these factors see Section C. Detailed discussion of these factors is presented in the state-of-the-art report.(1)

o Technical. The more common COM preparation involves dry grinding to obtain a coal-size distribution of 70 or 80 percent through 200 mesh. The pulverized coal is mixed with fuel oil in tanks equipped with a strong mechanical agitator. COM stability is a critical area. Stable coal-oil mixtures are required for successful storage handling and combustion. Stability can be achieved either by adding a chemical additive to the mixture or by using ultrafine (particle size less than 44 microns) coal. Both these measures have been successfully tried, and they suppress the hard packing of the coal in storage tanks. Extensive stability tests for the BCOM have not yet been conducted. However, it is expected that because of the low specific gravity of char particles, the settling rate will be lower compared to coal and therefore BCOM will face smaller stability problems than COM. These problems may be solved by using similar techniques (a chemical additive or ultrafine grinding) to enhance the stability of BCOM.

The viscosity of different concentration char-oil slurries as a function of temperature should be determined. It has been found that COM having coal concentration of more than 50 percent (by weight) exhibited non-Newtonian behavior. This may not be true for BCOM. The behavior of BCOM at different char/oil concentrations should be understood to avoid severe operational problems, which might occur in fuel lines, valves, strainers, heat exhangers, etc.

Boilers designed for oil or natural gas have relatively small furnace volume and the boiler tubes in the convection section have very narrow clearance. When COM is fired in such boilers, the inorganic constituents in the coal ash may form a slag on boiler heat-transfer surfaces.

However, for a BCOM containing low-ash char, this problem will be minimal. The use of soot blowers will alleviate the ash deposit problems.

Burner performance is a major concern when switching from fuel oil to COM or BCOM combustion. Recent combustion tests of COM in a utility boiler have shown rapid erosion of burner nozzles made of stainless steel in less than a week of service.(2) However, nozzles made of erosion-resistant material have performed well in long duration (more than 1,000 hours) tests.

o Environmental. The major environmental concern associated with the combustion of BCOM is particulate emissions. However, as the ash content of the char is very low, the particulate emissions from BCOM firing may not be significant. Therefore, a pollution control device like a baghouse may not be required. It should be noted that the ash that is produced from BCOM firing is very fine. A baghouse may therefore be more effective in reducing the particulate emission problem than a simple cyclone. Since the BCOM char is essentially free of sulfur, its use will actually reduce oxides of sulfur (SO_x) emission. Preliminary BCOM combustion tests have indicated reduced oxides of sulfur and also nitrogen emissions(1) compared to fuel oil burning alone.

o Socioeconomic and Institutional. A prerequisite for implementing BCOM combustion technology in developing countries is the successful implementation of a charcoal industry. Therefore, most of the social, economic, and institutional problems associated with the charcoal production industry, will also, indirectly, apply to BCOM combustion technology.

The rising cost of petroleum-derived fuels has given enough economic incentive that most of the fuel-oil-fired boiler operators in the U.S. are seriously considering switching to COM firing. Similar economic incentives are present today to justify an active technology development program for BCOM in developing countries. The experience gained in burning COM in the U.S. can be utilized in setting up pilot and demonstration projects for BCOM combustion. These projects should also include training programs for plant operators and the maintenance crew.

5. Future Development

As indicated earlier, most of the research and development work is currently focusing on improving the COM preparation, handling, and combustion techniques. At the present time, no separate efforts are being made to develop BCOM technology; however, the expectations are that most of the COM technology development work can be directly adopted for BCOM technology. For a detailed description of COM technology development activities, the reader is advised to refer to the state-of-the-art report.(1)

6. Product(s) Utilization

The biomass char-oil mixture is a slurried fuel containing about 40 to 50 percent by weight of finely ground (80 to 90 percent through 200 mesh) biomass-derived char and 60 to 50 percent by weight of residual oil. Lighter grade oils—distillate oil, for example—do not form a stable slurry or mixture with powdered coal. Thus, these oils may not be suitable for preparing BCOM. The relative proportion of char and residual oil will influence the major physical and chemical properties of BCOM fuels. Details regarding the physical and chemical properties and the combustion behavior of BCOM are presented in the state-of-the-art report.(1)

In recent combustion tests, BCOM burned similarly to residual fuel oil (see Section C). These encouraging results plus the successful commercial development of COM combustion technology suggest that the BCOM can be a potential substitute for petroleum-derived liquid fuels, particularly residual oil, in developing countries that are rich in forestry resources. Some potential applications of BCOM follow.

o As a Fuel for Steam/Power Production

The COM combustion technology is presently developed in the U.S. for retrofitting existing residual oil-fired boilers, both in the industrial and utility sectors (electricity generation). Therefore, the potential application of BCOM combustion technology, at least in the near term, should be restricted to residual-oil-fired boilers.

In general, the modifications that are necessary when retrofitting existing residual-oil-fired boilers to burn BCOM include:

— installation of new burner nozzles made of erosion-resistant material

— installation of a new fuel supply system, with parts contacting BCOM made from hardened steel

— installation of soot blowers, if not originally present, to keep the heat transfer surface clean

— installation of a particulate collection device (a baghouse or electrostatic precipitator) to clean the fuel gases, if needed

— installation of a new fuel receiving and storage system and a fuel preparation system if the BCOM is prepared onsite instead of purchased from a central facility.

Even after these modifications, the boiler, depending on its original design, may be derated in its normal steaming capacity when burning BCOM. This derating, if any, will be minimal. New facilities can be designed specifically to burn BCOM and will be easier to operate than retrofit systems.

o As a Fuel for Direct Residual-Oil-fired Equipment. BCOM can be burned in some direct residual-oil-fired industrial equipment. Typical examples of this equipment are: (a) blast furnace fuel injection*, (b) cement kilns, and (c) lime and brick kilns. The modifications necessary to retrofit existing residual-oil-fired equipment depend on the type of equipment under consideration. In general, they will be similar to those required for retrofitting boilers. However, if the existing combustion chamber or furnace has a large volume, as in the case of a blast furnace, longer residence times are available for the fuel in the combustion zone. This will allow coarser char particles in the BCOM.

o As a Fuel for the Internal Combustion Engine (Diesel Engine). The use of coal-oil mixture (COM) in diesel engines is at an early stage of development. Diesel engines are available in a variety of designs (see Section B). High-speed diesel engines typically use distillate oil (or diesel), while slow-speed diesels, which operate between 100 and 150 rpm, are designed for heavy residual oil.(3) Since distillate oil cannot form stable COM slurries, the high-speed diesel engines are not suitable for COM combustion. Preliminary short-term combustion tests have been conducted to burn COM in slow-speed diesel engines. These tests have established that a coal particle size on the order of a few microns is compatible with the combustion characteristics of the slow-speed diesel engines.(3) However, more research and development work is required to resolve:

— the incompatibility of conventional fuel-injection systems with coal-oil slurries

— the accelerated cylinder wear problems caused by ash deposits that interfere with lubrication of piston rings and cylinder walls.

---

*Applies when petroleum coke is used for pig iron production.

Once these problems are addressed, the COM combustion technology can be adapted to use BCOM in slow-speed diesel engines. This development will open up a large market for BCOM in developing countries. It should be observed that the abrasive properties of COM and BCOM are not the same.

References

1. Direct Combustion Systems to Produce Power from Biomass. AID Office of Energy, Washington, D.C. (in preparation).

2. "U.S. DOE Coal-Oil Mixture Combustion Program," C. B. Foster, paper presented at the Third International Symposium on Coal-Oil Mixture Combustion, Orlando, Florida, April 1981.

3. "Coal: Diesel Fuel of the Future," Power, vol. 125, pp. 45, March 1981.

HYDROLYSIS
A Technology to Produce Fermentable Sugars for Ethanol Production

1. Definition

Hydrolysis is a chemical and biological conversion of wood and other lignocellulosic feedstocks to fermentable sugars. Chemical processes use a mineral acid catalyst at relatively high pressures and temperatures to break large cellulose molecules into smaller sugar molecules, while biological processes use selective enzymes to break cellulose molecules into smaller sugar molecules.

2. Technical Description

Wood and other lignocellulosic feedstocks are composed of three distinct chemical fractions: hemicellulose, cellulose, and lignin. The hemicellulose fraction of wood hydrolyzes more readily than cellulose and yields mainly five carbon atom (pentose) sugars, the most common of which is xylose. The cellulose yields hexose (or six carbon atom) sugars of which glucose is the most common. During hydrolysis, the lignin fraction of wood virtually stays unchanged. The pentose sugars are not fermented to ethanol by the usual alcohol-producing yeasts. Therefore, if wood is being considered as a feedstock for ethanol production, it is desirable to remove pentose sugars by using a prehydrolysis (mild hydrolysis) step. If pentose sugars are not removed, they are largely destroyed during the hydrolysis of cellulose and can inhibit the subsequent ethanol fermentation.

The major cellulose hydrolysis processes can be categorized as concentrated acid hydrolysis, dilute acid hydrolysis, and enzymatic hydrolysis.

o Acid Hydrolysis. Acid hydrolysis processes, using both hydrochloric and sulfuric acid, were used commercially during World War II. Because of the special acid resistant processing equipment requirement and need for an acid recovery system, the concentrated acid hydrolysis process was not widely used. The most widely used process is the German Scholler process, where a dilute sulfuric acid promotes the hydrolysis of the cellulosic fraction of wood (or other lignocellulosic feedstocks) to produce fermentable sugars. The chemistry of this process is represented by the following simple reaction:

$$(C_6H_{10}O_5)_n + nH_2O \xrightarrow{[H+]} nC_6H_{12}O_6$$

(or: cellulose + steam or hot water in the presence of an acid catalyst yields fermentable sugars)

Briefly, during the Scholler acid hydrolysis process, biomass feedstock (materials containing a high cellulosic fraction) is fed into a vessel called digester. Then, steam is introduced to raise the feedstock and digester temperature. After attaining a certain specified temperature, a dilute sulfuric acid and previously hydrolyzed recycle stream are introduced into the digester, followed by the addition of hot water. The contents of the digester are kept at a constant temperature for a short residence time. During this time period, most of the hemicellulose fraction of biomass feedstock prehydrolyzes and it is removed from the digester. After the prehydrolysis, dilute sulfuric acid along with high pressure steam provides the necessary temperature and pressure for the main hydrolysis reaction, which converts most of the cellulosic fraction of the feedstock to fermentable sugars. Unlike prehydrolysis, longer residence time is used for the main hydrolysis reaction. After this reaction, the contents of the digester are brought back to atmospheric pressure in a couple of stages.

The Scholler process was modified by the Forest Products Laboratory (in Madison, Wisconsin, U.S.) during World War II. These modifications resulted in a shorter residence time for hydrolysis reactions, which prevented the excessive sugar degradation associated with the original Scholler process. Consequently, the Madison wood-sugar process yielded higher quantities of fermentable sugars.(1)*

o Enzymatic Hydrolysis. Certain types of enzymes are capable of hydrolyzing cellulose to fermentable sugars. However, the cellulose present in wood or wood waste is relatively immune to attack by selected enzymes. This resistance to enzymatic hydrolysis comes from the close physical and chemical association between cellulose, hemicellulose and lignin. Several thermochemical and chemical pretreatment processes are capable of breaking up the lignocellulose complex, thus providing access to the cellulosic molecules and facilitating enzymatic hydrolysis processes.

For details regarding hydrolysis processes see the state-of-the-art report.(1)

3. Current Status of the Technology

Acid hydrolysis of cellulose has been practiced in the past, and some industrial-scale and development plants exist outside the United States. About 44 plants using Scholler-Madison technology are reported to operate in the U.S.S.R. (Russia), and demonstration plants have been built and operated in Japan.(2) Most of the research and development efforts on acid hydrolysis in the U.S. are focused on determining optimum hydrolysis conditions and sugar and by-product yields. Alternative acid hydrolysis techniques are being tested using small-scale prototype hydrolysis reactors. Several pilot and demonstration projects are currently in the design stage.

In an effort to supplement the current sugar cane-based ethanol (ethyl alcohol) production capacity, Brazil is looking to wood as a raw material. Serious consideration is being given to the construction of a commercial plant for acid hydrolysis of wood based on Russian technology. A detailed engineering equipment and construction phase of the project was initiated in 1981.(1)

Enzymatic hydrolysis is at an advanced stage of commercial development. Research and development activities are focused on developing inexpensive and recyclable enzymes.

4. Technology Issues and Problems

Acid hydrolysis technology was successfully used in Germany prior to and during World War II. Also, some plants were operated in Sweden, Switzerland, Japan, U.S.S.R., Korea, and the United States. Except for those in U.S.S.R., all of these plants have since been abandoned for technical and economic reasons.(2)

o Technical. As previously stated, wood is composed of three fractions: hemicellulose, cellulose, and lignin. Hemicellulose is readily hydrolyzed under mild conditions compared to cellulose. Strong acid hydrolysis conditions, capable of hydrolyzing the cellulose, destroy the sugars formed from the more easily hydrolyzed hemicellulose. If milder hydrolysis conditions are used to avoid this destructive effect, incomplete cellulose hydrolysis takes place. In either case, the yields of sugar are very low. This is a major technical limitation of acid hydrolysis technology developed prior to World War II. Selective removal of sugars (five carbon atom sugars) obtainable from the hemicellulose fraction of wood can improve the overall sugar yields of the hydrolysis process. Several mechanical and thermal treatments can also increase the sugar yields.(1) Hydrolysis processes using concentrated acids require careful selection of process equipment and materials of construction; the acid recovery system needs to be carefully operated for efficient acid utilization.

---

* Numbers in parentheses refer to numbered references listed at the end of this subsection.

Enzymatic hydrolysis requires mechanical and/or chemical pretreatment for promoting the cellulose conversion to fermentable sugars (glucose). As the concentration of sugar increases in the hydrolysis vessel, the activity of enzymes currently available is reduced. The sugar solutions must therefore be removed continuously or periodically to maintain enzyme activity. The concentration of this diluted sugar solution is too low for direct ethanol fermentation (see Ethanol Fermentation). For economic ethanol fermentation, the sugar concentration in the dilute hydrolysis product stream should be increased by removing large quantities of water by evaporation.(2) This requirement will impose a substantial energy penalty on the overall conversion (wood to sugars to ethanol) scheme.

o Environmental. Disposal of the neutralized salts produced during acid hydrolysis will be required. The effluent water stream from the plant will contain soluble organic compounds, such as acetic acid and methanol. This untreated water will be high in biological oxygen demand (BOD), an indicator of water pollution. This water will have to be treated to reduce the BOD. If hydrochloric acid is used for hydrolysis, its vapor might create an air pollution problem.

Enzymatic hydrolysis using acid pretreatment will produce inorganic salts, for which disposal will also be required. In addition, the water effluent from enzymatic hydrolysis will have to be treated to reduce the BOD.

o Socioeconomic and Institutional. Acid hydrolysis of wood and other cellulosic feedstock has not been tried in developing countries, with the exception of Korea. It is for all practical purposes a new technology for the developing country environment. Most of the equipment associated with this technology may have to be imported from developed countries, making demands on already scarce foreign exchange resources. Careful evaluation should be made of the potential net benefits to be gained by implementing this technology in replacing a part of petroleum-derived fuels. A skilled labor force will be required for the successful operation of hydrolysis plants.

The economic competitiveness of the hydrolysis process to produce fermentable sugars and their subsequent fermentation to ethanol depends on the marketability of by-products produced during the process. Also, the high cost of currently available enzymes makes the enzymatic hydrolysis economically unattractive.

Finally, a widespread use of wood hydrolysis technology may affect the availability of fuelwood for residential and industrial use in many developing countries. However, countries like Brazil, with large wood resources, may not face this problem.

5. Future Development. Recent research and development efforts in acid hydrolysis technology have focused on increasing the sugar yields by using high temperature and pressure processes. At these conditions, shorter residence times are possible which will reduce the equipment size for desired output. Also, efforts are underway to improve the separation of fermentable sugars from the unconverted residue and lignin stream. Conversion of the lignin fraction to more valuable products, instead of its use as in-plant fuel, is also being considered. For example, Brazil is considering wood acid hydrolysis plants where the lignin residue will be carbonized to form lignin charcoal which can be used in the iron ore smelting.

Several mechanical and chemical pretreatment processes are being developed to facilitate the enzymatic hydrolysis process. Also, less expensive enzyme production and recovery techniques are being developed. The five carbon atom sugars (pentose sugar), a product obtained from the prehydrolysis of the hemicellulose fraction of biomass, cannot be fermented to ethanol using conventional yeasts. Processes are, however, being developed to convert pentose sugar solution into ethanol.(1) This development will improve the overall yield of ethanol obtained from biomass feedstock such as wood and crop residue.

6. Product(s) Utilization

The main product of both acid and enzymatic hydrolysis of lignocellulose feedstocks, is a solution of fermentable sugars, which can be used to produce ethanol. The by-products of this process can be used to produce a variety of fuels and chemicals. The yield of the fermentable sugars and other by-products for different hydrolysis conditions and feedstocks is given in the state-of-the-art report.(1) Also, some of these data are presented in Section C.

o The Main Product as a Feed for Fermentation to Ethanol. The product of hydrolysis of wood and crop residue is a solution of glucose sugar, which can be converted to ethanol by using conventional yeasts (see Fermentation to Ethanol). The ethanol, in turn, can be used to substitute petroleum-derived fuels in different sectors of developing countries (see Fermentation to Ethanol). The sugar solution produced by the enzymatic hydrolysis can be directly used for ethanol production. However, the fermentable sugars produced during the acid hydrolysis process contain inhibitory substances which significantly retard the rate of ethanol fermentation.(1) The exact nature of these substances is not known. It is, however, believed that they are produced as a result of hemicellulose and cellulose degradation and metal corrosion.(1) The rate of ethanol fermentation can be improved by effective cleaning of the sugar solutions. Even after this cleanup, it is expected that the rate of ethanol fermentation may not be as fast as that obtained from other readily fermentable sugar solutions, i.e., sugars derived from starchy and sugary feedstocks.

o By-products for Fuels and Chemicals. The by-product pentose sugars (five carbon sugars) can be converted directly to furfural. Hydrogenation of a portion of the lignin fraction will yield phenols and higher phenols. Alternatively, the lignin fraction can be gasified to produce synthesis gas (see Gasification) or hydrocracked to benzene, toluene, and xylene.

References

1. Alcohol Fuels: Ethanol, Methanol and their Use. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

2. Technology and Economics of Conversion of Cellulose (Wood) and Corn Starch to Sugars, Alcohol and Yeast, B. Wolnak, Bernard Wolnak and Associates. USDOE, Chicago, Illinois, U.S. August 1978.

FERMENTATION TO ETHANOL
A Technology to Produce Fuel Ethanol (Ethyl Alcohol)

1. Definition

Fermentation is a biological process that converts fermentable sugar solutions into a dilute ethanol solution (6 to 12 percent ethanol) by specially selected strains of yeast. This dilute alcohol solution is called "beer." It is heated to remove the product alcohol by distillation. Fuel-grade ethanol (greater than 99 percent purity) is obtained by further distillation in the presence of some chemical solvents.

2. Technology Description

The overall fermentation reaction can be represented by the following simple equations:

$$\underset{\text{(sucrose)}}{C_{12}H_{22}O_{11}} \xrightarrow{\text{enzyme}} \underset{\text{(glucose)}}{2C_6H_{12}O_6}$$

$$\underset{\text{(glucose)}}{C_6H_{12}O_6} \xrightarrow{\text{yeast}} \underset{\text{(ethanol)}}{2C_2H_5OH} + 2CO_2$$

This system is a great simplification of the total reactions involved in the process. However, it illustrates the major chemical conversion steps required for the production of ethanol from sugar solutions.

Bioresources containing hexose sugar (six carbon atom sugars) or materials that can be easily converted into hexose sugar are ideal feedstocks for ethanol fermentation. These resources include foods such as sugar beets, sugar, molasses, corn, potatoes, and other grains. Fermentation of fruits and grains to produce beverage alcohol has been used for centuries. Even today all beverage alcohol is produced through the fermentation of cereal grains, molasses, and other materials with high starch and sugar content. Cellulosic materials, i.e., crop residue, wood and wood waste, after extensive pretreatment and hydrolysis (see Hydrolysis) can be converted into fermentable sugars. Thus, these materials can be indirectly used for ethanol fermentation.

The major steps required to convert sugars to alcohol by yeast are:(1)*

- preparation of the sugar solution (mash)
- preparation of yeast cultures
- fermentation
- separation of products
- distillation

Nonsugary feedstocks, starch and cellulose, require extensive preprocessing (i.e., hydrolysis) before the ethanol production steps are followed.

The first step in the sugar fermentation is the preparation of an aqueous solution having a sugar concentration conducive for yeast fermentation. This aqueous solution is called "mash." This solution is kept acidic by adding sulfuric acid to provide maximum antibacterial action, which protects the yeast and promotes the fermentation process. In some cases, yeast nutrients are also used to increase the rate and efficiency of the fermentation process. The yeast cultures are specially prepared to tolerate high nonsugar solid concentrations and high temperatures. During the ethanol production, the yeast cells are recovered after completion of the fermentation period by centrifuging them out of the fermented mash. The recovered yeast is washed with sulfuric acid before being used in another fermentation cycle.

Fermentation of the mash, a 48-hour process, takes place in cylindrical tanks called fermenters. The fermenters are arranged in batteries. As the mash is charged into a fermentation tank, yeast is added to commence the fermentation process. The process heat must be drawn off to maintain the mash temperatures at or below a predetermined level to avoid any yeast deactivation. The carbon dioxide produced during fermentation may be discharged into the atmosphere or dried and compressed into marketable forms when feasible.

---

*Numbers in parentheses refer to numbered references listed at the end of this subsection.

The fermented mash, containing up to 12 percent alcohol, is passed through a centrifuge; the clarified beer, is pumped to the beer-holding tank, and yeast is diverted to a separate tank for recovery. The clarified beer is charged into the beer still where initial ethanol distillation takes place. The alcohol now 50 percent in water vapors, boils off the top and condenses for further purification. The bottoms from the beer still, i.e., stillage, can be concentrated by evaporation and finally dried in a rotary dryer.

The beer-still distillates (condensed vapors of 50 percent alcohol in water) are introduced into one or more distillation columns to remove small quantities of aldehydes and higher alcohols (fusel oil) and to concentrate the alcohol to 95 percent (190 proof). The production of anhydrous ethanol, 100 percent or 200 proof, requires the removal of the remaining water by a special distillation (i.e., azeotropic distillation) process. In this process, benzene or another suitable material is added to the 190 proof alcohol to allow the anhydrous ethanol to be separated from the remaining water by distillation process. The product, fuel ethanol (i.e., anhydrous ethanol), is sent to the storage tanks.

Details regarding the production of ethanol from sugar crops can be found in the state-of-the-art report.(2) However, selected information and data extracted from the literature sources used in preparing this state-of-the-art report are presented in Section C.

3. Current Status of the Technology

The production of ethanol by the fermentation of sugars and starches has been practiced for centuries. Until the end of World War II, the fermentation of molasses, fruits, and grains was the main source of ethanol in the U.S. and other countries. Fermentation of grains, fruits, and sugars is still the only source of ethanol produced for human consumption.

Also, ethanol produced from the fermentation of grains and sugars is currently being blended with gasoline and used as motor fuel in both the U.S. and Brazil. The use of these blends is practiced on a limited scale in the U.S. and on a much wider scale in Brazil. American blends usually use ethanol from grain fermentation while Brazil's alcohol comes primarily from sugar cane.

The conventional ethanol production technology is based on batch and semi-continuous operations. The motor fuel production schemes use an improved version of this beverage alcohol production technology. These improvements generally focus on reducing the length of the fermentation period and the energy required for separating product ethanol (i.e., distillation). Advanced continuous fermentation processes are currently being developed, and they may soon be available for commercial application. Research and development work is also presently proceeding on continuous fermentation processes operating under subatmospheric pressures or in a vacuum. In addition, major research and development efforts are currently underway at several research centers in the U.S. and other parts of the world to develop improved technology for conversion of cellulosic wastes (i.e., wood, urban waste, crop residue) to sugars, which, in turn, can be fermented to ethanol.

4. Technology Issues and Problems

Even though sugar (or grain) fermentation is an old and proven technology, its successful application for ethanol fuel production requires some technical improvements in the conventional processing scheme. Also, economical, institutional, and social constraints of this technology, if any, may affect its successful implementation in developing countries. For more information and data on the factors discussed here, see Section C and the state-of-the-art report.(2)

o Technical. Fuel-grade ethanol should be completely free of water to avoid any difficulty in its application as a blend in an internal combustion engine (see Product(s) Utilization). This is particularly true when an ethanol-gasoline blend is being considered for automobile fuel application. The conventional ethanol fermentation scheme requires large quantities of heat energy for upgrading the dilute ethanol solution, produced during fermentation, to the final anhydrous fuel-grade ethanol product. When conventional petroleum-derived fuels are used to supply this energy, the overall energy balance of such an ethanol production scheme becomes quite unfavorable, i.e., the energy contained in a unit of product ethanol becomes less than the energy required to produce that unit. This unfavorable energy balance of a conventional ethanol fermentation scheme can severely constrain the wide-scale use of ethanol as a petroleum-derived fuel substitute. One way to resolve this energy balance issue is to use coal or other solid fuels, like wood and crop residue, to supply the in-plant energy needs of ethanol fermentation plants. Also, technical improvements in the energy-intensive processing steps, particularly distillation, will significantly decrease the energy requirements for fuel-grade ethanol production.

The technology of converting cellulosic feedstocks, like wood, crop residue, and preprocessed urban solid waste, to sugars is still being developed, and it has not proceeded far enough to justify immediate implementation of full-scale plants. The major problems of this technology (i.e., hydrolysis) are: (a) lower yields of fermentable sugars, (b) acid corrosion and recovery (for acid hydrolysis), and (c) nonavailability of inexpensive high-activity enzymes (for enzymatic hydrolysis). For further discussion of this technology see Hydrolysis in Section A.

Finally, the potential contamination of the fermentation process by undesirable microorganisms poses a serious operating problem because it deactivates the yeast, which can drastically reduce the yield of ethanol. To avoid any contamination, the fermentation equipment has to be kept completely sterile. This requirement in itself complicates the development of a continuous fermentation technology.

o Environmental. The effluent from the initial distillation step (beer distillation) in ethanol production from sugar cane juice and molasses is called stillage. It is very high in biological and chemical oxygen demand, which are indicators of water pollution. Hence, it poses a serious pollution threat if it is discharged untreated into bodies of surface water. However, various methods of treatment and disposal are available, and in some cases the untreated stillage can be an excellent source of fertilizer.(2) In the case of grain fermentation, the stillage is a valuable feed by-product because of its protein content.

Water needs of large-scale fermentation plants are substantial, and this could present problems in dry regions.

o Socioeconomic and Institutional. The widespread use of ethanol produced from sugar and starch crops will affect the supply of human food and/or animal feed. These crops grow on high quality land, and any major grain or sugar-based ethanol program will affect the agricultural sector—farm income, land prices, and the commodity sector price of grains and of cattle feed. Also, the diversion of sugar crops to ethanol production will reduce or eliminate the foreign exchange earnings when the international sugar price is high. Therefore, careful evaluation should be conducted to weigh the benefits of potential reduction in

SECTION B

INTERMEDIATE CONVERSION PROCESSES

In some cases, fuels and energy products obtained from biomass conversion processes are more useful if further converted to a different energy form. For example, steam produced from the direct combustion of biomass (or fossil fuels*) may be more useful if converted to electricity. Or, synthesis gas produced by the gasification of biomass (or fossil fuels) may be more useful as methanol. Steam is converted to electricity by means of a steam turbine and synthesis gas to methanol by methanol synthesis. These additional conversion steps are called intermediate conversion processes. The intermediate conversion processes described in this section are:

- Steam turbines
- Gas turbine engines
- Internal combustion engines
- Methanol synthesis
- Mobil (Methanol) M-gasoline synthesis
- Fischer-Tropsch synthesis (indirect liquefaction)

Processes are described according to their:

1. Technical Description and Present Use
2. Potential Use of Biomass Derived Fuels and Energy Products
3. Future Development

---

*Intermediate conversion processes are applicable to fuels and energy products obtained from both biomass and fossil fuels.

engines cannot be run directly on ethanol because of its unsuitable ignition qualities* (low cetane number). It is possible, however, to carry out modifications to produce a spark-assisted diesel engine that can be adapted for alcohol use.

- o As a Fuel for Gas Turbines. Gas turbines burn natural gas and lighter liquid fuels to produce mechanical power. If electricity is the desired product, then a generator can be hooked to the turbine (see Section B). Gas turbines are generally larger and designed to deliver more power than internal combustion engines. They are typically used in electric power generating plants, gas and oil pumping stations, natural gas liquefaction plants, and jet aircraft.

Ethanol can be burned in existing stationary gas turbines after proper modifications. Its lower energy density, however, makes it an undesirable fuel for aircraft gas turbines. There is currently no commercial utilization of ethanol as a gas turbine fuel. However, the feasibility of ethanol use in turbines is being studied by the Brazilian government. The use of alcohol fuels in the stationary gas turbines is technically feasible. The combustion chamber, fuel control, and handling system of existing turbines should be retrofitted to burn ethanol. The ease of this retrofit depends on the original design of the turbine (see Section B).

The availability and high cost of ethanol compared with that of conventional fuels are major barriers to its expanded use in gas turbines.

References

1. Technology and Economics of Conversion of Cellulose (Wood) and Corn Starch to Sugars, Alcohol, and Yeast, B. Wolnak, Bernard Wolnak and Associates. USDOE, Chicago, Illinois, U.S. August 1978.

2. Alcohol Fuels: Ethanol, Methanol and their Use. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

3. Small-Scale Fuel Alcohol Production, U.S. Department of Agriculture, Washington, D.C., March 1980.

4. Fuel From Farms - A Guide to Small-Scale Ethanol Production, Solar Energy Research Institute, SERI/SP-451-519, UC-61, Golden, CO., February 1980.

---

* Fuels with lower cetane number do not self-ignite at higher pressures.

petroleum imports against the loss of foreign exchange earnings due to decline in sugar production.

5. Future Development

Advances in ethanol fermentation technology will focus on the development of continuous fermentation processes and alternative, low energy-consuming alcohol recovery (i.e., dehydration) schemes. Continuous fermentation processes operating in a vacuum use the heat generated by fermentation reaction to distill off the alcohol. This results in reducing the need for fermenter cooling water, improving the rate of fermentation reaction and yields, and reducing the overall energy consumption—in effect, reducing the investment and operating costs of fermentation. However, such processes are still in the laboratory at pilot-scale development and are not likely to be commercially available in the near future.(2)

Research and development efforts are continuing on alternatives to the distillation method of separating alcohol from water. The use of solid dessicants for dehydration of ethanol is one of the methods that is being actively pursued. Other methods such as liquid-liquid extraction, reverse osmosis, and ultrafiltration are being developed on a laboratory scale. These alternative ethanol dehydrating techniques, if successfully developed, can greatly reduce the energy consumption for ethanol production.

Lastly, different chemical and biological processes are being developed to convert cellulosic feedstocks, like wood or wood waste, crop residue, and preprocessed municipal solid waste, to fermentable sugars (see Hydrolysis). These improved processes are primarily geared towards increasing the sugar yields and reducing intensive pretreatments so that an economical cellulose-based ethanol production scheme can be developed.

6. Product(s) Utilization

Commercial-grade ethanol (ethyl alcohol) contains approximately 5 percent water. Pure ethanol is produced by a special processing step (azeotropic distillation) and it is essentially free of water. It is a volatile, flammable, clear, colorless liquid. The energy content (or heating value) of pure ethanol is about 60 percent of the energy content of conventional petroleum-derived liquid fuels (gasoline). It can be blended with gasoline and used as an automobile fuel without any engine modifications. Also, it can be substituted for other conventional petroleum-derived fuels after proper engine and other combustion equipment modifications. Potential applications of ethanol fuel in developing countries are briefly presented in the following sections. For quantitative data on ethanol production and use, see Section C.

o As a Fuel for Internal Combustion Engines. Ethanol can be used in spark-ignition (SI) engines after some necessary engine modification (see Internal Combustion Engines in Section B). However, alcohol- gasoline blends, up to 10 percent alcohol by volume, can be used in conventional automobiles without any engine modifications. Only blends obtained by using anhydrous ethanol (pure ethanol) are suitable for trouble-free engine operation. This is because the presence of small quantities of water promotes phase separation which is undesirable because the engine fails to perform frequently and is subjected to corrosion.(2) New engines, specifically designed to burn ethanol, can operate on ethanol containing up to 20 percent water. These ethanol-only engines are being installed in Brazilian vehicles. Major automobile manufacturers such as Volkswagen, Fiat, and Ford are manufacturing the engines.(2)

The stationary diesel engine is a vital component of rural energy supply system in many developing countries. Diesel engines are also used in trucks, buses, and other automobiles. Conventional diesel

STEAM TURBINES
A Technology to Use Steam to Power a Rotating Shaft

1. Technical Description and Present Use

Steam turbines expand steam to lower pressures, producing mechanical work which can be used to run many process machines and electrical generators. Nozzles are used for steam expansion. Two methods of expansion are generally employed: (a) impulse, and (b) reaction.

The impulse turbine expands the steam in stationary nozzles, where higher velocities are attained. The steam jet then flows over moving rotor blades without further expansion. These blades rotate the turbine shaft, which can be hooked to an electrical generator to produce electricity or hooked to run process machines. The reaction turbine expands the steam both in the fixed and moving blades, and the steam pressure is greater at the inlet than the outlet edges of the blades. Both design features can be used in a single turbine.

Steam turbines are broadly classed as either condensing or noncondensing turbines. Condensing turbines expand the inlet steam to pressures below atmospheric pressure, whereas noncondensing turbines expand to pressures above atmospheric pressure. Special turbine designs (extraction, for example) are available wherein part of the steam leaves the turbine at pressures above the exhaust (outlet) pressure. This intermediate-pressure steam is generally used for boiler feed water heating and also to supply process heat in an industrial application. This simultaneous production of power and process heat is called cogeneration, which is becoming popular because of its high overall energy conversion efficiency.

Steam turbine capacities range from 1 kW to over 800,000 kW (1.3 hp to 1,100,000 hp). Steam inlet pressure ranges from 136 to 34,421 kPa (5 to 5,000 psig) and temperatures from saturated at the pressure to 566°C (1,050°F). Speed for small machines can go higher than 10,000 rpm.* Whereas speeds for large- and intermediate-size machines are generally 1,800 and 3,600 rpm, respectively, speed-reducing gears can be used to make the turbine speed compatible with the speed of electric generators and other industrial turbomachinery, such as pumps and compressors.

Small turbines up to 745 kW (1,000 hp) power rating are single-stage units and are generally designed to operate in a noncondensing mode. The main use of these turbines is to drive power plant auxiliaries, such as centrifugal pumps, fans, blowers, and small generator sets to produce electricity. They may also be used to supply mechanical power and/or electricity for industrial plants. These turbines are best suited for running small electrical generators in the rural areas of developing countries to supply the local electric power needs.

Multistage turbines are generally designed for power outputs greater than 745 kW (1,000 hp). Small units of this type use a straight condensing steam cycle, whereas medium and large turbines extract part of the inlet steam for boiler feed water heating. The medium-size turbines (less than 50,000 kW or 67,114 hp) in the U.S. are generally used for running electric generators in small power plants, producing mechanical power (running compressors, pumps, etc.), electricity, and process heat for industry. The large-size turbines (more than 100,000 kW or 134,228 hp) are most commonly used in large central electric power stations.

The turbine performance can be measured by steam rate, which is the amount (kg or lb) of steam per hour required to produce a unit (kW or hp) of mechanical power. The steam rate is an overall indicator of how efficiently a turbine is converting the heat energy contained in steam to mechanical power. The heat energy in steam is known as its enthalpy, which increases as the pressure and temperature of steam increases. Therefore, high pressure and temperature steam has more energy available per unit of mass than its low counterpart. Thus, turbines using high-pressure, superheated steam give lower steam rates than the ones using low pressure, saturated steam. Also, the steam rate for noncondensing turbines is generally higher than a comparable-size condensing turbine. However, the heat contained in the exhaust steam from a noncondensing turbine can be recovered, whereas the heat contained in the exhaust steam from a condensing unit is lost in the condenser. In end-use applications, where low-level heat of the exhaust steam can be used, the noncondensing unit can give a higher overall thermal efficiency than the condensing unit.

---

*Revolutions per minute.

2. Potential Uses of Biomass-Derived Fuels and Energy Products

Steam turbines use steam only as the driving fluid, which can be produced by the direct combustion of a variety of fuels, including the direct combustion of biomass feedstocks (see Direct Combustion in Section A). The turbine type and design are essentially determined by the intended end-use application (mechanical, power, electricity, or process heat). The steam conditions, both pressure and temperature, also influence the selection of a particular turbine.

o Low-Pressure Steam. Smaller biomass fired boilers are generally designed to produce low-pressure saturated steam (see Direct Combustion in Section A). The steam produced from these boilers can be used in single-stage turbines to produce mechanical power to run small industrial equipment or to run small electrical generators for electricity production. These turbines are generally the noncondensing type, which are easier to operate and maintain than the condensing type. They are preferable for small steam turbine plants in developing countries.

Most of the steam turbines require a very dry steam. Even the presence of a few percentage points of water vapor in the inlet steam can be detrimental to the turbine performance. Therefore, the quality of steam from biomass-fired boilers, particularly fire tube boilers (see Direct Combustion in Section A), should be carefully controlled.

o High-Pressure Steam. High pressure, superheated steam can be produced in intermediate- to large-size biomass-fired boilers, particularly wood-fired boilers (see Direct Combustion in Section A). This steam can be used in multistage turbines to run industrial equipment and electrical generators. The most common use of high pressure, superheated steam is in electric power generation, where multistage turbines expand the steam to lower pressures, producing mechanical work which, in turn, is used to run electrical generators to produce electricity. These multistage turbines are generally condensing-type units; the exhaust steam from these units is condensed by using cooling water. The condensed water, after necessary cleanup (polishing), is sent to the boiler feed water system where, after the addition of make-up water, it goes back to the boiler for steam generation.

The use of steam turbine systems to produce electricity, in addition to a source of steam (generally a boiler plant), also requires steam condensing and cooling water systems. In areas where water availability is not a problem, once-through cooling is possible. However, in water-scarce areas, recycling of cooling water is necessary. This is generally accomplished by using cooling towers. An alternative is to use air, instead of water, for exhaust steam condensation.

The availability and transportability limitations of biomass resources dictate the maximum size of a biomass- or wood-fired power plant. In the U.S., where large forest resources are available and actively managed, wood-fired power plants of 50,000 kW capacity are considered to be the largest feasible units. In the wood-rich developing countries, the wood-fired power plants will be a great deal smaller than the above capacity, unless large tree plantations are dedicated solely to supplying a power plant. The actual capacity of these plants will depend on the resource availability and in-country electric power supply situation.

3. Future Development

Steam turbine technology is an old and highly developed technology. Most technical developments have been realized and successfully used in current design. Some research and development efforts currently focus on development of materials that can withstand temperatures higher than 649°C (1,200°F). This development will improve the overall thermal efficiency of electric power generation.

Because of the low-heat and high-moisture content of biomass feedstocks, biomass-fired (or wood-fired) boilers cannot produce high-temperature steam. Therefore, the above-mentioned development will not benefit the biomass-based electricity generation scheme.

GAS TURBINE ENGINES
A Technology to Convert the Chemical Energy Contained in Gaseous or Liquid Fuels to Mechanical and Electrical Power

1. Technical Description and Present Use

The gas turbine engine uses continuous-flow compression, heat addition, and expansion processes to produce mechanical work. Atmospheric air is compressed in a multistage, axial- and/or centrifugal-flow compressor and is then mixed and burned with fuel in a combustor. The high-pressure-hot-combustion gas is then expanded through a multistage, axial flow turbine and exhausts to the atmosphere. The expansion process produces mechanical power. A portion of this turbine mechanical work drives the air compressor and the remaining power (the net output power) drives an external load such as the electric generator.

The overall efficiency (net output divided by fuel input energy) of the gas turbine engine depends mainly on the compressor pressure ratio, the turbine inlet temperature, and the parasitic losses—especially the compressor and turbine efficiencies. For the theoretical case of an ideal gas turbine with no internal parasitic losses, overall efficiency increases solely with increasing pressure ratio. For a real gas turbine with losses, overall efficiency depends also on turbine inlet temperature, since higher temperature means increased useful power output and a proportionate reduction in the effect of internal losses.

Overall efficiencies of gas turbines currently available range from 25 to 35 percent. Compressor pressure ratios range from 10 to 20 and turbine inlet temperatures range from 1,037°C to 1,148°C (1,900°F to 2,100°F). At these turbine inlet temperatures, the turbine rotating blades and fixed-nozzle vanes must be cooled to maintain safe metal temperatures. In current machines, cooling air is bled from the compressor and piped through internal passages in the turbine blades and nozzles. The cooling air exits the blades and vanes through small holes and mixes with the mainstream of hot combustion gas.

The gas turbine has a very flexible power cycle. Gas turbines are currently being offered in the 10 MW to 85 MW capacity range. While not quite as efficient as the diesel engine, the gas turbine is noted for its low capital cost. In its simplest form, the gas turbine is small, light, requires only a modest foundation and building, does not require cooling water, runs unattended, and can be remotely or automatically controlled. It is capable of rapid start-up and loading. Gas turbines can be arranged to supply power, high pressure air, or hot exhaust gas, either singly or in combination.

In recent years, gas turbines have been combined with steam turbines. Such an arrangement is called a combined-cycle system. The expanded combustion products leave the gas turbine at a rather high temperature, generally about 538°C (1,000°F). Aproximately 75 percent of the useful heat in the exhaust gas can be recovered in a waste heat steam boiler. The superheated steam generated by the gas turbine exhaust is expanded in a steam turbine to produce additional power. Current-technology combined cycles (gas turbine and steam turbine) have overall efficiencies of from 42 to 46 percent.

Gas turbines have mainly used natural gas and light distillate oils as fuels. Fuels containing sulfur, salt, or (as in the case of residual oil) vanadium or other metals will cause corrosion unless waterwashed to remove salt and treated with additives to inhibit the corrosion mechanism. With the proper fuel treatment, gas turbines have operated on a wide range of liquid and gas fuels. Gas turbines are currently being designed to operate on coal-derived fuels. These same or similar fuels could also be derived from wood or other organic substances. Biomass-operated gas turbines may face many operational problems caused by the dust and particulate deposits on turbine impellers, resulting in balancing problems. For this reason, direct use of biomass has been very limited.

2. Potential Uses of Biomass-Derived Fuels and Energy Products

Although gas turbines have mainly used natural gas and clean petroleum fuels, a few gas turbines have used alcohol and coal liquids and gases. Biomass-derived fuels can be substituted for these fuels after matching the fuel characteristics with the gas turbines' combustor and fuel supply system. If the biomass fuel is similar in heating value and flammability to the conventional gas turbine fuels, then minimal modifications are required to existing, "off-the-shelf" equipment. Fuels with lower heating values will require, at a minimum, a redesigned fuel nozzle to obtain the larger flow rates required. For fuels which do not satisfy the flammability requirement, it is often possible to enrich the mixture by blending with small amounts of broad-range flammability gases. The adaptability of biomass-derived fuels is presented below.

o Liquid Fuels. A variety of liquid fuels can be produced from biomass. Some of these are methanol, ethanol, pyrolytic oil, and vegetable oil. Methanol and ethanol are excellent gas turbine fuels. They are chemically pure and have a relatively low flame temperature. Methanol and ethanol exhibit lower emissions of nitrogen oxides than natural gas or petroleum fuels. The only substantial problems with methanol and ethanol are their low heating values. For a given turbine inlet temperature, the required fuel-to-air ratios of these alcohol fuels are about twice that of natural gas. The fuel delivery system, fuel nozzle and combustor would have to be designed to accomodate the increased fuel flow.

Pyrolytic oil and vegetable oil can be burned in gas turbines. These oils, however, have higher viscosities and lower heating values than conventional petroleum distillates. Also, pyrolytic oil has corrosive properties. The fuel delivery system and combustion system would have to be modified to accommodate these characteristics.

o Gaseous Fuel. Common gaseous fuels produced from biomass include biogas, medium-heat-value gas, low-heat-value gas (producer gas), and pyrolytic gas. The pyrolytic gases may require extensive cleaning before they can be used in gas turbines. The other gaseous fuels can be used after minor cleanup. The presence of alkali metal salts in biomass-derived gaseous fuels may corrode turbine blades.

Medium-heat-value gases (about 11,190 kJ/m^3 or 300 Btu/scf) present a problem due to their relatively high flame temperatures. The main constituents of these fuels, hydrogen and carbon monoxide, have flame temperatures greater than 2,371°C (4,300°F). High flame temperatures cause the formation of oxides of nitrogen in the combustor primary zone. The oxides of nitrogen produced from the combustion of medium-heat-value gas can be greater than that from the combustion of oil and natural gas.

Low-heat-value fuel gases (about 5,595 kJ/m^3 or 150 Btu/scf) pose problems due to their very low heating values, reduced flame temperatures, changing flammability limits, and reduced chemical reaction rates. In addition, a low-heat-value gas combustor would have to be capable of operation on a high heat-value conventional fuel such as distillate oil. Low-heat-value-gas-fueled turbines may be integrally tied to the advanced wood gasification process, providing compressed air to the gasifier and receiving fuel gas directly from the cleanup system. During power plant startup, the gas turbine will have to operate on an alternate fuel before the gasification system reaches normal operation. It will also be required that gas turbine operation be maintained during an upset of the fuel gas system. If fuel gas production is reduced, it will be necessary that dual fuel operation be available if required. Dual fuel capability is provided by the use of two sets of fuel piping to feed a combustor head containing concentric fuel nozzles.

When compared to conventional, high-heat-value fuel burners, low-heat-value combustors are larger in volume and contain large fuel nozzles to accomodate the tenfold increases in fuel-air ratio needed when burning low-heat-value gas. The large volume is also required to provide the longer reaction times needed for combustion of the large amount of carbon monoxide in the low-heat-value gas.

3. Future Development

Advanced gas turbine designs are being developed to burn liquid and gaseous fuels derived from coal. One such development is the integration of a coal gasification plant with a combined-cycle gas turbine plant. Combined-cycle plants use both gas and steam turbines to improve the overall plant thermal efficiency. This concept has been successfully tested at pilot scale, and commercial-size plants are expected to be operating by 1984 in the U.S. The experience gained in burning coal-derived fuel gases in gas turbines can be directly applied to the combustion of low- and medium-heat-value gases produced from biomass gasification.

INTERNAL COMBUSTION ENGINES
A Technology to use the Chemical Energy of Gaseous or Liquid Fuels to Power a Rotating Shaft

1. Technical Description and Present Use

Internal combustion (IC) reciprocating engines burn a fuel/air mixture to produce mechanical work. The mixture is first compressed in a cylinder by a moving piston and then ignites (or is ignited) and expands to push the piston and supply mechanical energy. IC engines are commonly divided into two types:

- spark ignition (SI) or Otto cycle engines, commonly fueled with gasoline
- compression ignition (CI) or diesel cycle engines, commonly fueled with fuel oil

In the SI engine a premixed fuel/air mixture is introduced into the cylinder, compressed by the piston, and ignited by a spark plug as the piston nears the top of its stroke. Other factors being equal, the engine efficiency is primarily determined by the compression ratio, the ratio of the cylinder volumes when the piston is at the bottom vs. the top of its stroke. A higher compression ratio would yield higher engine efficiency. The compression ratio is limited, however, by the propensity of the fuel to self-ignite before the spark plug fires. The ability of the fuel to avoid self-ignition is indicated by its octane number. A fuel with a high octane number will resist self-ignition allowing a high compression ratio and high engine efficiency. Existing SI engines operate with a compression ratio in the range of 6:1 to 12:1 producing pressures from 1,034 kPa to above 2,068 kPa (150 to 300 psi). Fuel mixing is achieved with carburetors, gas-mixing valves, or fuel injection systems. Gasoline-fueled SI engines are commonly used in sizes from fractional kilowatt (horsepower) to large marine and truck engine sizes. Large SI engines in stationary applications may also be fueled with natural gas, coke-oven gas, and producer gas. In diesel (CI) engines, the fuel is injected directly into the cylinder just as the piston nears the top of its stroke. The fuel ignites from the heat of the compressed air in the cylinder. In most cases no ignition devices are used so the fuel must be one which will self-ignite under these conditions. The ability of the fuel to self-ignite is indicated by its cetane number. A high cetane number indicates good self-ignition characteristics. In some cases, when self-ignition cannot be achieved, a dual-fuel engine may be used which uses a small amount of high cetane number "pilot fuel" to initiate combustion.

Compression ratios in diesel engines must be high in order to ensure combustion. Compression ratios of 11.5:1 to 22:1 are typical. They produce pressures of 2,760 kPa to 4,820 kPa (400 to 700 psi). Diesel engines typically are used in larger sizes than SI engines. Common applications of diesel engines include trucks, buses, and large marine engines as well as prime movers for stationary applications (up to multimegawatt size).

Internal combustion engines provide the bulk of the stationary power needs, particularly in the rural areas of developing countries. Diesel engines, by far, are more commonly used than other types of internal combustion engines. These engines power irrigation pumps and run sawmills, grain mills, and electric generators to supply power for rural communities. Also many small-scale rural industries use diesel engines for their power needs.

2. Potential Uses of Biomass-Derived Fuels and Energy Products

Biomass-derived fuels, in most cases, can be substituted for conventional fuels after proper engine modifications. Depending on the type of engine and biomass-derived fuel, modifications may range from simple to complex. A discussion of the adaptability of biomass-derived fuels follows.

o Liquid Fuel. Some of the major fuels that can be produced from biomass are methanol, ethanol, pyrolytic oil, and veg- etable oil. See Section A for a further discussion of the synthesis of these fuels.

Methanol and ethanol are promising fuels for SI engines. These alcohols have been used in a neat (pure) form and blended with gasoline. SI engines must be altered slightly to use neat alcohols because of the lower air/fuel ratio required for their combustion. Engines designed for methanol are about 20% more efficient than corresponding gasoline engines. However, alcohol/gasoline blends, up to 10 percent alcohol by volume, can be used in conventional automobiles without any difficulty. Some problems of degradation of plastic parts, and corrosion of fuel tanks have been observed when using gasohol in engines not designed originally for gasohol use. These blends are currently being used on a limited scale in the U.S. and on a much wider scale in Brazil. American blends usually use ethanol from grain, and Brazil's alcohol comes primarily from sugar cane.

Methanol blends have not been as popular as ethanol blends. This is because of methanol's lower heating value, lower tolerance for water, toxicity relative to ethanol, and lack of biomass-based production processes.

Alcohols are not suitable for conventional diesel engines because of their low cetane number. However, spark assisted diesel engines can burn neat (pure) alcohols. Sunflower seed oil and a variety of vegetable and plant oils can also be burned in diesel engines. These oils, however, have higher viscosities and lower heating values than conventional diesel fuels. Pyrolytic oils are unsuitable for diesel engines.

For quantitative information on the use of biomass-derived liquid fuels in internal combustion engines, see Section C.

o Gaseous Fuel. Common gaseous fuels produced from biomass include biogas produced through anaerobic digestion of biomass, low-heat-value gas (producer gas) and medium-heat-value gas (synthesis gas) generated through gasification of biomass, and pyrolytic gas, a low-heat- value gas obtained during the process of pyrolysis of biomass. The biogas, medium- heat-value and producer gases can be used in existing gas or gasoline engines after minor cleanup. The gasifier-produced gases, however, must be cooled before use in the engines. Pyrolytic gases may require extensive cleaning before they can be used in existing engines. In the case of gas engines, the biomass-derived gaseous fuels can be directly used in existing engines. For gasoline engines, however, a fuel-air mixer needs to be installed preceding the carburetor. In both cases, depending on the heating value of the fuel, the existing engine will produce less power than its rated capacity for conventional fuels. This derating will be minimal for biogas when compared with either producer or pyrolytic gas because of its high heating value.

As indicated earlier, the diesel engine is the most commonly used internal combustion engine in the rural areas of developing countries. Unlike SI engines, diesel engines have to be retrofitted to use biomass-derived gaseous fuels. The ease of retrofit depends upon the type of engine and gaseous fuel under consideration. There are two principal retrofit methods:

1. Installation of an extra magneto and a spark plug to assist ignition. This conversion method permits the engine to use biomass-derived gaseous fuels entirely. However, in most of the existing engines, there is not a proper place to install the magneto and spark plugs; this is particularly true for the smaller engines.

2. Adoption of the dual-fuel method. The conversion of great numbers of small diesel engines in rural areas of developing countries to dual fuel (biomass-based gas and diesel) engines

is a practical and efficient method, and maintenance is simple. It involves installation of an extra fuel-mixing device at the rear of the air filter.

Dual-fuel internal combustion (diesel) engines can use both liquid fuels and mixed fuels. Gas is the primary fuel, and diesel oil is used to ignite the gas-air mixture. In case the gas fuel is not sufficient to meet an engine's needs, it can be quickly and simply switched to diesel fuel.

Dual-fuel engines are now used in several developing countries. The most notable applications are in sewage treatment plants and in generating electricity in rural areas. The extent of derating of existing engines, when converted to operate a dual-fuel mode will depend on the type of biomass-derived gas and the fraction of original diesel in the mixed fuel. As indicated earlier, the derating will be minimal for biogas when compared with producer (or low-heat-value), medium-heat-value, and pyrolytic gases.

3. Future Development

The introduction of an alcohol fuel, both ethanol and methanol, engine employing spark ignition at a high compression ratio will help promote the extended use of alcohol fuels in internal combustion engines, particularly automotive engines.

The possibility of elevating cetane numbers, by adding ignition enhancers, provides an opportunity to make alcohol fuels compatible with diesel engines. However, the effects of these additives on alcohol fuels should be explored. In addition, the use of alcohol in diesel engines has been attempted using several fuel-mixing techniques. The use of alcohol and diesel fuel emulsions is one of the promising techniques. Methanol and ethanol microemulsion studies indicate that savings in diesel fuel can be realized both from energy replacement and thermal efficiency improvements.

Finally, developmental work is also focusing on using slurries as fuel for diesel engines. These engines, when successfully developed, will burn pulverized solid fuels (char and sawdust) in combination with conventional petroleum- derived liquid fuels.

METHANOL SYNTHESIS
A Technology to Convert
Medium-Heat Gas (Synthesis Gas)
to
Methanol Fuel

1. Technical Description and Present Use

The synthesis of methanol (methyl alcohol) from carbon monoxide and hydrogen is an established industrial process. Conventional high-pressure synthesis, which was discovered in 1923, is carried out at pressures around 30.4 MPa (300 atm). Chrome oxide/zinc oxide catalysts are generally used in the high-pressure synthesis that convert the carbon monoxide and hydrogen-rich gas mixture, known as synthesis gas, at temperatures between 320°C and 380°C (608°F and 716°F) according to the following equation:

$$CO + 2H_2 \longrightarrow CH_3OH$$

In a carbon monoxide and hydrogen reaction system many other reactions can also take place. For example, higher alcohols, formaldehyde, methane, and other heavier hydrocarbons can potentially form during methanol synthesis. The operating conditions, i.e., temperature and pressure, and use of a selective catalyst suppress the formation of these undesirable products. A large portion of the carbon dioxide present in the system, either coming from the synthesis gas or produced during the methanol synthesis, is converted to methanol by the following equation:

$$CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O$$

The major achievement in the methanol synthesis technology was the development of a low-pressure process. In the 1960s, ICI developed a new copper-based catalyst that is much more active than the conventional chrome oxide/zinc oxide catalyst at low pressures. The development of this highly active copper catalyst made it possible for the methanol synthesis reaction to take place at low pressures in the range of 5.1 to 10.3 MPa (750 to 1,500 psi). Since the development, many commercial methanol synthesis plants, have been designed, constructed, and successfully operated. In all the new methanol plant construction, the low-pressure technology is being used.

In the low-pressure methanol process a crude synthesis gas, a product of steam reforming of natural gas or partial oxidation of petroleum-derived fuels, is cleaned, compressed to about 2.7 MPa (400 psi), and then passed through a shift conversion step where a catalytic reaction converts part of carbon monoxide to additional hydrogen. This conversion step adjusts the H_2/CO ratio in the synthesis gas. The shifted gas goes to the purification system after waste-heat recovery, where a hot-carbonate scrubbing system is used to remove the acid gases, particularly hydrogen sulfide down to a 10 ppm level. The copper-based catalyst, used in the low-pressure process, is very sensitive to any sulfur impurities present in the synthesis gas. Effective sulfur removal should be practiced to avoid any downstream catalyst poisoning. The carbon dioxide content of the synthesis gas is reduced to 7 percent (by volume) so that the ratio of $H_2/(CO+1.5\ CO_2) = 2.05$ in the gas can be achieved. This is considered to be an optimum ratio for methanol synthesis from a feed gas containing hydrogen, CO, and small quantities of CO_2.

The sulfur-free synthesis gas is compressed from about 2.6 MPa (385 psi) to 10.3 MPa (1,500 psi) and combined with recycle gas to pass through a fixed-bed catalytic converter to produce crude methanol. As the methanol conversion reaction proceeds, large quantities of heat are released, which should be removed immediately to avoid any catalyst deactivation. The heat is removed by injecting a sufficient amount of cool inlet gas mixture (i.e., synthesis gas) between the catalyst beds. Also, conversion per pass is restricted to less than 15 percent (by volume) of inlet gases; thus, the heat released per pass is proportionately reduced. The effluent gases from the converter are cooled and crude methanol is condensed and transfered to the refining section, while the uncondensed gases are recycled to the suction side of the recycle compressor and mixed with feed gas. Some of the recycle gas is purged to control the concentration of inert components in the converter system. This purged gas stream is used as an in-plant fuel. The crude methanol is purified as required by distillation to produce fuel-grade or chemical-grade methanol.

Currently, methanol synthesis is exclusively used in the chemical industry, where the product methanol is used in the production of other chemicals (particularly formaldehyde) and solvents. The use of methanol as a fuel is not practiced at the present time. However, methanol is considered to be a potentially attractive substitute for petroleum-derived liquid fuels (see Internal Combustion Engines and Gas Turbines). It also offers the potential of direct gasoline synthesis (see Mobil (Methanol) M-Gasoline Synthesis).

The synthesis gas (a mixture of carbon monoxide and hydrogen) required for methanol synthesis can be produced from a variety of carbonaceous feedstocks. The methanol plants around the world today use natural gas, naphtha (a lighter petroleum derivative), and fuel oil as the common feedstocks. Because of the dwindling supplies of the commonly used feedstocks, the use of coal gasification to produce synthesis gas for methanol production is seriously considered at the present time. The gasification of certain biomass feedstocks can also produce a synthesis gas suitable for methanol production (see Gasification in Section A). The potential use of such a gas in methanol synthesis follows.

2. Potential Uses of Biomass-Derived Fuels and Energy Products

Synthesis gas produced by biomass gasification can be used in methanol synthesis after proper conditioning. Gas conditioning includes cleanup of the crude synthesis gas from the gasifier to remove particulate matter, water. vapors, and condensable tars (see Gasification in Section A). After this cleanup, the composition of the gas is adjusted so that a predetermined hydrogen-to-carbon monoxide ratio is obtained. Also, the concentration of carbon dioxide is reduced, and any sulfur compounds are completely removed. The techniques used for conditioning the crude synthesis gas are similar to those described earlier for conventional feedstocks. Because of the low sulfur content of biomass feedstocks, especially wood, the concentration of sulfur compounds in the wood-based synthesis gas will be minimal.

To avoid nitrogen dilution of the feed gas, oxygen gasifiers instead of air-blown gasifiers should be used. Since the methanol synthesis takes place at relatively high pressures, gasifiers operating at high pressures are suitable for methanol plants. This type of biomass gasifier is still in the pilot-scale testing and development phase. They are expected to be ready for commercial application by the mid-eighties.

The use of biomass-derived synthesis gas to produce methanol has been considered in the past. For example, a wood-to-methanol pilot plant, producing about 5 tonne/day (5.5 ton/day) of methanol from about 16 tonne/day (17.6 ton/day) of dry wood, was operated in France during 1944 to 1945.(1) In Brazil, large-scale methanol production using synthesis gas obtained from wood gasification is now being considered. Detailed engineering designs for a demonstration plant are currently underway, and the plant is scheduled to start up some time during 1982.(1)

Methanol plants using conventional feedstocks, natural gas, or fuel oil have been built for capacities as large as 1,800 tonne/day (2,000 ton/day) of product methanol. Similar capacities are possible for plants using coal as the primary feedstock. However, because of the dispersed nature of biomass feedstocks, the maximum capacities of biomass-based methanol plants will be smaller than the above-mentioned capacities. It is expected that biomass-based methanol plants will produce less than 400 tonne/day (441 ton/day) of methanol. Only wood-rich countries will be able to meet the feedstock demand of such plants.

3. Future Development

Present day methanol technology is well developed. The use of a highly active copper-based catalyst has cut the operating pressures of conventional processes by at least a factor of three. Research and development efforts are still underway to develop a superactive catalyst that can promote methanol synthesis reaction even at lower pressures. Lower pressure synthesis provides for better process integration with existing biomass gasifiers, resulting in energy savings and improving the thermal efficiency of the overall process.(1) These energy savings can be realized because of the low compressor power requirement.

The development of a liquid-phase methanol synthesis process provides a better heat-removal technique than that employed in the present processes. This will result in higher conversion per pass, increased reaction rate, and reduced recycle gas rate.(1) The liquid phase synthesis is at an advanced stage of development. Finally, the successful commercialization of the Mobil methanol-to-gasoline process (see Mobil (Methanol) M-Gasoline Synthesis) will accelerate the use of methanol as a commercial petroleum-derived fuel substitute.

References

1. Gasification: Small and Large Systems and their Use. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

MOBIL (METHANOL) M-GASOLINE SYNTHESIS

A Technology to Convert Methanol to High-Octane Gasoline

1. Technical Description and Present Use

Mobil Research and Development Corporation, New Jersey, U.S., has developed a process in which methanol is directly converted to a high-octane gasoline. This process is the M-gasoline process. It offers an opportunity to indirectly convert biomass into gasoline range hydrocarbons. The major steps involved in such a conversion scheme are:

- production of synthesis gas, a suitable mixture of hydrogen and carbon monoxide, from biomass feedstocks (see Gasification in Section A)
- conversion of synthesis gas to methanol (see Methanol Synthesis)
- conversion of methanol to gasoline range hydrocarbons by the M-gasoline process

In the M-gasoline process, methanol is catalytically dehydrated to dimethyl ether which is polymerized to gasoline-range hydrocarbons. These two conversion steps are carried out in fixed-bed reactors. Feed methanol, containing 16 percent water (by weight), is vaporized by heat exchange with reactor effluent and also by heat input from the feed heater. Vaporized methanol is catalytically converted to a mixture of dimethyl ether and water in the first reactor.(1)* The reactor effluent, containing dimethyl ether, unconverted methanol and water, is combined with recycled product gas and flows to the second reactor where a shape-selective zeolite catalyst completes the conversion to hydrocarbons and water. The overall reaction for methanol conversion to gasoline-range hydrocarbons can be given by the following equation:

$$n\mathrm{CH_3OH} \;——\; (\mathrm{CH_2})_n + n\mathrm{H_2O}$$

The reaction is highly exothermic, heat is released as the reaction proceeds, and about 20 to 30 percent of the total heat released occurs in the first reactor. This reactor is operated adiabatically with a maximum temperature rise of 93°C (200°F). The temperature rise in the second reactor is kept between 38°C to 93°C (100°F to 200°F). A recycle gas system is used to control temperature in both reactors. The reactor effluent from the second stage is condensed, and the water and liquid hydrocarbon phases separated, a portion of the gas is recycled for reactor cooling.(1)

The operating pressure in both reactors is kept around 2.0 MPa (285 psi), and the temperature range between 316°C to 454°C (600°F to 850°F). Methanol conversion efficiencies of greater than 99.0 percent are obtained; the overall thermal efficiency is around 94.0 percent. Because of coke deposition, the catalyst deactivates after several weeks of operation. It is then regenerated by burning off accumulated coke.

The M-gasoline process has been successfully tested in a 636 L/day (4 bbl/day) process development unit, and a conceptual design of a 15,900 L/day (100 bbl/day) pilot plant has been completed.(2) Recently it was announced that New Zealand was proceeding with plans for a 1.98×10^6 L/day (12,500 bbl/day) plant to convert natural gas to gasoline via methanol. Commercial development of the process is based on a fixed-bed reactor. Process development studies are concentrating on a dense fluidized-bed reactor.(2)

2. Potential Uses of Biomass-Derived Fuels and Energy Products

As indicated earlier, the synthesis gas produced by biomass gasification can be converted to methanol (see Methanol Synthesis), which, in turn, can be converted to synthetic gasoline by the M-gasoline process. This route offers an opportunity for biomasss feedstocks, particularly wood, to be indirectly converted to gasoline.

---

* Numbers in parentheses refer to numbered references listed at the end of this subsection.

However, a prerequisite for this route is the successful development of high-pressure, oxygen-blown wood gasifiers (see Gasification) which will facilitate the production of methanol from biomass. Because of the availability and transportability limitations of biomass feedstocks, particularly wood, the maximum capacity of a wood-to-methanol to-M-gasoline plant will be restricted to about 159,000 L/day (1,000 bbl/day) of gasoline. These lower capacities may not be able to take advantage of the economies of scale in plant investment and thus may not be cost competitive with large coal- or natural gas-based plants. In wood-rich countries, where either of these fossil resources are not available, the wood-to-gasoline via methanol route can be considered.

The major product of M-gasoline process is synthetic gasoline which is similar to gasoline produced by petroleum refining. The octane rating of this synthetic gasoline exceeds the current requirements of commercial gasoline products in the U.S. The by-products, olefins and isobutane, produced during the M-gasoline synthesis are separated and alkylated to additional gasoline.(1)

Because the methanol feed does not contain any sulfur or nitrogen, the product gasoline contains no sulfur or nitrogen. However, the gasoline does contain durene, an alkyl benzene, in significant quantities. Conventional gasoline contains durene in very small quantities. Durene has a high octane number, boils in the same range as gasoline (197°C or 386°F), but has a freezing point of 79°C (175°F). Therefore, the presence of durene might cause problems by crystallizing out in an engine's carburetor.

The production rate of durene can be decreased to its allowable concentration in gasoline by various controllable process parameters. As an alternative, gasoline containing higher than allowable durene levels could be blended with the conventional gasoline.

3. Future Development

The methanol-to-gasoline conversion reaction is highly exothermic with the heat of reaction being about 1,720 kJ/kg (740 Btu/lb) of methanol. The main problem in designing the M-gasoline reactor system is heat removal. In the commercial design concept a fixed-bed reactor system is used where the heat removal is facilitated by dividing the overall reaction into two steps. A gas recycle system is used to remove the heat released during these two conversion steps. This heat removal system has been well demonstrated and can be readily enlarged.(3)

Advanced reactor systems, such as quenched reactor, tubular heat exchange reactor, or fluidized-bed reactor can be developed to solve the heat removal problems associated with the present fixed-bed design. Also, the present commercial design concept has not been tried in an actual commercial operating plant. It is expected that a commercial-scale plant will be operating in New Zealand by 1985. The successful commercial application of M-gasoline technology will enhance the opportunities for its integration with a biomass-based methanol production scheme (see Methanol Synthesis).

References

1. "Coal Liquefaction Process Research Process Survey R&D," Interim Report, Data Source Book, prepared by the Ralph M. Parsons Company, Pasadena, California, U.S., for USDOE, December 1977.

2. Gasification: Small and Large Systems and their Use. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

3. Research Guidance Studies to Assess Gasoline from Coal by Methanol-to-Gasoline and Sasol-type Fischer-Tropsch Technologies, Max Schreiner, Mobil Research and Development Corporation, Princeton, New Jersey, August 1978.

FISCHER-TROPSCH SYNTHESIS
A Technology to
Convert Medium-Heat-Value Gas to Hydrocarbon Products

1. Technical Description and Present Use

The Fischer-Tropsch (F-T) synthesis, essentially, is the catalytic conversion of synthesis gas, which is a suitable mixture of hydrogen and carbon monoxide, to hydrocarbons like olefins and linear paraffins. Cobalt-, iron-, nickel-, and ruthenium-based catalysts are used. The F-T synthesis is carried out at pressures below 10 MPa (1,500 psi) and temperatures below 350°C (986°F). A wide variety of fuels and chemicals are obtained from F-T synthesis. Relative proportions of these compounds depend on the catalyst type and operating conditions chosen. The overall chemistry of the F-T synthesis of paraffinic and olefinic hydrocarbons may be presented by the following equations:(1)*

- Reactions to paraffinic hydrocarbons:

$$nCO + (2n+1)H_2 \;\text{—}\; C_nH_{2n+2} + nH_2O$$

$$2nCO + (n+1)H_2 \;\text{—}\; C_nH_{2n+2} + nCO_2$$

- Reactions to olefinic hydrocarbons:

$$nCO + 2nH_2 \;\_\; C_nH_{2n} + nH_2O$$

$$2nCO + nH_2 \;\_\; C_nH_{2n} + nCO_2$$

The main synthesis reactions are highly exothermic, releasing large quantities of heat as the reactions proceed. Very close temperature control is required during the synthesis to supress methane formation. Both fixed- and fluidized-bed types of reactors have been used.

In the fixed-bed process, synthesis gas at 250°C (480°F) and at 2.5 MPa (365 psi) enters the top of the reactor and passes over an iron catalyst enclosed in tubes. Outside the tube, high-pressure steam is produced using the exothermic heat of reaction, thus controlling the temperature of the reactor. This process is primarily used to produce diesel oil and wax fractions.(1)

The fluidized-bed process is used to produce lighter products such as gasoline and fuel gas. In this process, hot-feed synthesis gas and powdered-iron catalyst enter the bottom of the reactor and pass up through a reaction zone and then a cooling section. In the cooling section, the gas passes through tubes that are cooled on the outside by a circulating oil stream. Gas then leaves the reactor and passes through cyclone separators where entrained catalyst is removed. The recovered catalyst from the cyclone is mixed with feed gas just upstream of the reactor. Operating conditions of the fluidized-bed reactor are 2 MPa (295 psi), 330°C (630°F), and a gas velocity of 1.2 to 2.1 m (4 to 7 ft) per second.(1)

Because of the lack of catalyst selectivity, the F-T synthesis produces a wide range of hydrocarbons. These hydrocarbons, however, are similar to different petroleum-derived fuels and chemicals. Most of the hydrocarbon products obtained from the F-T synthesis are not directly usable, and conventional petroleum refining techniques are employed to convert these products to more specific fuels such as gasoline, diesel, and fuel oil.

The F-T synthesis was used successfully in Germany during World War II to produce a variety of fuels and chemicals. In the early 1950s, the U.S. Bureau of Mines operated a 7,950 L (50 bbl) per day pilot plant using the F-T process at Louisiana, Missouri. A commercial plant in Brownsville, Texas, also was operated for a short period at about the same time. It produced about 1.1×10^6 L (7,000 bbl) per day of liquid fuels and chemicals using natural gas as feedstock.(2) The major commercial successful application of this technology has been the Sasol complex in South Africa. The first plant, Sasol I, has been operated commercially since 1956. Sasol II, a larger plant, recently went on stream at the end of 1980. A third plant, Sasol III, which is essentially a duplicate of Sasol II, is scheduled to begin operating in late 1982.(3) At the Sasol complex, the synthesis gas used in the F-T synthesis is produced by coal gasification.

---

* Numbers in parentheses refer to numbered references listed at the end of this subsection.

The synthesis gas required for F-T synthesis can also be produced by the gasification of biomass feedstocks (see Gasification in Section A). The use of biomass-derived gas is described below.

2. Potential Uses of Biomass-Derived Fuels and Energy Products

Synthesis gas obtained from the oxygen-blown gasification of biomass (see Gasification in Section A), after proper conditioning, can be used in the F-T synthesis. For both the fixed- and fluidized-bed processes, the hydrogen-to-carbon monoxide ratio required in the synthesis gas is around 3 to 1. The crude synthesis gas, a product of biomass gasification, will have to be cleaned and shifted to obtain a proper hydrogen-to-carbon monoxide ratio for the F-T synthesis. Since most of the existing biomass gasifiers operate at lower pressures, the clean synthesis may be required to be compressed to the F-T synthesis pressures. Development of high-pressure biomass gasifiers will eliminate such compression requirements and improve the overall thermal efficiency of biomass- based F-T synthesis.

Large quantities of biomass feedstocks will be required for gasification to produce synthesis gas for F-T synthesis. This biomass feedstock requirement can be only met by wood and wood waste resources (forest resources). Because of the availability and transportability limitations of biomass feedstocks, even the largest biomass-based F-T synthesis plant will be smaller than their coal or natural gas-based counterparts. The F-T synthesis products need to be upgraded before they can be substituted for conventional petroleum-derived products. This upgrading involves highly complex plants with substantial equipment needs which makes the F-T synthesis plant highly capital intensive. In the case of a biomass-based F-T synthesis plant, this problem will be further aggravated by the lack of economies of scale in plant investment resulting from small-scale operation. Therefore, the biomass-based F-T synthesis will not be cost competitive with coal or natural gas-based substitutes.

3. Future Development

Current research and development on the F-T synthesis focus on developing a more selective catalyst to reduce the amount of downstream refining and upgrading required.(1)

Recent research has indicated that significant improvements in product selectivity for the F-T synthesis may be possible. Molecular-sieve zeolites appear to have the ability to limit the molecular weight of the hydrocarbons produced. They also can apparently increase the yield of isoparaffins and aromatics. Ruthenium-alumina catalysts also show potential for limiting the size of the molecules produced as do catalysts containing copper-nickel (Cu-Ni) alloys. Most of these studies have been aimed at increasing the yield of gasoline from the F-T synthesis. Mobil is developing a series of catalysts that they believe can reduce the cost of gasoline from the F-T synthesis by 20 percent. These catalysts are composed of a typical F-T metal and a zeolite of the ZSM-5 class.(1)

References

1. Gasification: Small and Large Systems and their Use. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

2. Assessment of Technology for the Liquifaction of Coal: Summary, National Academy of Sciences, Washington, D.C. 1977.

3. "C_1 Chemistry Development Intensifies," Chemical and Engineering News, pp. 39-47, February 28, 1981.

SECTION C

BIOMASS TECHNOLOGY DATA

This section contains technical, economic, environmental, and institutional data on eight biomass conversion technologies that produce substitute fuels and/or energy products. Data were abstracted from selected literature sources used in the preparation of the individual state-of-the-art reports listed in the Foreword. The abstracts here are called "entry statements." They are organized in three major paragraphs according to how data relates to the technologys:

1. Viability
2. Implementation
3. Environmental Factors

The paragraph on viability factors includes a summary of relevant biomass feedstocks, energy product(s) derived from the feedstocks, technology used, yields, operating conditions, costs (capital and operating), markets for the derived-energy products, profitability statements and their origins.

Implementation refers to those factors that concern institutional support, project coordination with national goals and interests, national capability, training of labor force in requisite skills and financial ability, market penetration features, price competitiveness, competitive products, and technical and cultural appropriateness or acceptability issues.

Environmental factors relate to land use, including preservation and multiple-use issues; water use, including preservation and pollution; atmosphere, including pollution, climatic factors, and regulations; and ecology, including the interrelationships of all of the above factors and their effects on the human population.

Three additional paragraphs contain:

4. Related Literature Citations
5. Objective Observations on the Literature Source Cited
6. Subjective Observations on the Literature Source Cited

Because of the scope of this project and budgetary constraints, a limited number of entry statements are presented for each technology area at this time. It is anticipated that more entry statements will be prepared later for inclusion in this handbook.

Also, in order to facilitate future updating procedures, each technology area in this section has been allocated one hundred pages; it is envisioned that this number will be adequate for any future inclusion and updating requirement of the material presented in this handbook. Because of this provision, each technology area in this section begins with a page number in a new series (e.g., C-101, C-201, C-301).

ANAEROBIC DIGESTION

Detailed data on the technology for digestion of residues to methane are presented in:

> Anaerobic Digestion: Biogas Production and Uses. A State-of-the-Art Review. USAID Office of Energy, Washington, D.C. (in preparation).

Selected data on methane fermentation technology are found in the entry statements in this section. The entry statement index, Table C-I, is designed to aid readers in their search for specific data entries. The location of entry statements and the corresponding literature sources are indicated in Table C-II.

TABLE C-I

ENTRY STATEMENT INDEX FOR RESIDUE DIGESTION TO METHANE

Source of Data (Country):	Entry Number:
China	1, 2
Thailand	3
Ecuador	4
India	5
U.S.	6
Data Type:	
Commercial systems	
- Small	1, 3, 4, 5
- Large	2
- Pilot/Demonstration	6
Biomass Feedstocks:	
Animal or human waste	1,2,3,4,5,6
Crop Residue	1, 4
Sewage	2

TABLE C-II

SOURCE AND LOCATION OF ENTRY STATEMENTS

Entry Statement Number and Page		Literature Source
1	C-103	"The Use of Water Pressure Digesters in China," Chen Ru-chen and Xiao Zhi-ping, in Fuel Gas Production from Biomass, Volume I, edited by D. L. Wise, CRC Press Inc., Boca Raton, FL, 1981, pp. 147-154.
2	C-104	"A Biogas Power Station in Foshan, China," Chen Ru-Chen, Huang Cong and Xiao Zhi-ping, in Fuel Gas Production from Biomass, edited by D. L. Wise, CRC Press Inc., Boca Raton, FA., 1981, pp. 225-232.
3	C-106	"Biomethanation of Manure and Agricultural Residues in Thailand. Thai Cement Water Jar as a Biomethanation Unit," National Energy Administration, Pibultham Villa, Bangkok 5, Thailand, June 1980.
4	C-107	"Biomass Program Assessment and Planning in Ecuador," J. A. Brautigam and R. T. Skrinde, Report to USDA Forest Service-Biomass Energy Team-USAID Office of Energy, Olympic Associates, Seattle, WA, April 1981.
5	C-108	"BIO-GAS: Achievements and Challenges," M. A. Sathianathan, published by Association of Voluntary Agencies for Rural Development, A/1 Kailash Colony, New Delhi-110048, June 1975.
6	C-110	"Report on the Design and Operation of a Full-Scale Anaerobic Dairy Manure Digester," E. Coppinger, J. Brautigam, J. Lenart, and D. Baylon, Final Report, U.S. Department of Energy, Contract No. EG-77-C-01-4042, SERI/TR-312-471, December 1979.

ENTRY STATEMENT NO. 1

1. VIABILITY FACTORS: Most of the family-size digesters built in China operate on the water pressure principle. In a common version of the unit, the circular main digester chamber covered with a fixed domed roof is partially filled with slurry. As biogas is produced, pressure builds up and the slurry is pushed out of the main chamber into an adjacent vertical outlet chamber connected to the main chamber. When biogas is used, slurry flows back into the main chamber, thereby maintaining a relatively constant pressure in the digester. Other designs of rectangular shape include internal baffles to isolate the main digester section from the outlet chamber.

Advantages of the Chinese water pressure digester include: the use of a fixed roof eliminates the need for expensive metal floating covers common to many other designs; the use of local materials and construction techniques adapted to soil conditions reduces construction costs; underground construction reduces the effect of ambient temperature variations on the rate of digestion; and the system can accomodate fairly high percentages of fibrous feedstocks.

The main disadvantages of the Chinese units are leakage of gas despite cement or plaster coating of the masonry chamber, loss of the gas generated in the outlet chamber and potential blockage as the slurry flows in and out of the digester when the concentration of solids is too high. The latter problem is prevented by using diluted slurries. A recommended slurry composition includes 10 percent human wastes, 30 percent animal wastes, 10 percent plant material and 50 percent water by volume. Dilution of the slurry is probably partially responsible for the low gas-production rate in the digesters. The average gas-production rate reported for small units in the Guangdong Province is 0.15 cubic meter of biogas per cubic meter of reactor per day. Production rates can vary between 0.04 to 0.07 cubic meter of biogas per cubic meter reactor per day in winter and 0.5 cubic meter per cubic meter per day in summer.

A typical family of five requires about 1 cubic meter of gas per day for cooking and boiling water. Digesters of 6 to 10 cubic meters can fulfill these needs. The construction of a 6-cubic meter unit requires about 370 kg of cement, 90 kg of lime, 1.7 cubic meters of sand, 0.7 cubic meter of gravel and 800 (24 x 12 x 6 cm) bricks; alternatively, the unit can be built with about 230 kg of cement, 350 kg of lime, 1.4 cubic meters of sand, 0.7 cubic meter of gravel and 170 bricks. Construction requires about 30 man-days. The actual cost of construction will depend on the availability and cost of construction materials in individual countries. Some difficulties in construction and operation of water pressure digesters of large size (up to 50 or 60 cubic meters) have been encountered. Designs involving plastic (PV) balloon gas holders are being tested.

2. IMPLEMENTATION FACTORS: The Chinese government has popularized biogas technology in the rural areas of the country. For example, it instituted several educational and technology transfer programs where the users learn all aspects of the technology through documentary films, television programs, a biogas manual, etc. The biogas manual points out the special care that has to be taken in both constructing and operating digesters. Since 1970, 7 million digesters have been installed in China. The use of biogas in rural areas has reduced the demand for scarce firewood and straw, the traditional fuels in those areas. Further, tens of work days previously spent yearly by every family to gather fuelwood have become available for more productive activities.

3. ENVIRONMENTAL FACTORS: Biogas generation helps kill off disease-causing organisms, greatly improving hygienic conditions in rural areas, and the sludge produced is free from the odor normally associated with manure piles and pits. The

use of a particular digester design reportedly has resulted in a reduction of 98 percent of the parasite eggs present in human wastes fed to the unit.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: A Chinese Biogas Manual. Translated by Michael Cook and edited by Atiane Van Buren, Intermediate Technology Group, London, 1979.

Observation of Fuel Gas Production in Asia, R. T. Skrinde, in Fuel Gas Production from Biomass, Volume I, editor D. L. Wise, CRC Press, Inc. Boca Raton, FL., 1981.

5. OBJECTIVE OBSERVATIONS: The effect of digester size on the investment and its performance is not discussed. Also, biogas performance data for different feedstock mixes and different temperatures are not provided.

6. SUBJECTIVE OBSERVATIONS: No relevant observations.

ENTRY STATEMENT NO. 2

1. VIABILITY FACTORS: A waste treatment plant in Foshan, Guangdong, China, originally designed to treat human wastes and to provide fertilizer was converted into a biogas power station with an output of 90 kW.

The treatment plant comprises 28 rectangular tanks of 47 cubic meters each, which were converted into digesters. The bottoms and covers are made of concrete and the walls are made of bricks. To prevent gas leakage, the covers are coated with mixes of cement and polyvinyl acetate latex and bituminous paint as a protection against corrosion. Gas is stored at low pressure (3 cm of water) in two 120-cubic-meter balloons made of PVC film 0.28 mm thick. The storage balloons are surrounded by a protective enclosure. One 50-kW diesel engine-generator unit was modified to spark ignition operation to use biogas fuel. A 40-kW gasoline engine used biogas without modifications.

Night soil is fed at a rate of 60 tons per day, while an equivalent quantity of digested sludge is discharged by gravity to fertilizer barges. The dry material content of the night soil is 2 percent and the volatile solids content is 1.7 percent. The retention time is 22 days. During summer, the temperature of the digester is 30°C and gas is produced at a rate of 0.3 cubic meter per cubic meter of reactor per day without stirring. With stirring, the rate increases to 0.55 cubic meter per cubic meter per day. In winter (3 to 4 months of the year), the temperature reaches 14°C, and gas production is about one-half that of the summer rate. The biogas contains 71 to 72 percent CH_4, 26 to 27 percent CO_2 and traces of H_2S. In the case of the gas engine-generator unit, 1 cubic meter of biogas at standard temperature and pressure provides 1.73 kWh of electricity for an overall conversion efficiency of about 24.3 percent. The converted plant has operated since 1974. Scum layers are found in the digester; these layers contain undigested organic matter. Stirring may resolve this problem.

Stirring the contents of the digester almost doubles gas production. About 14 percent of the supplementary gas produced through stirring is required to provide energy for stirring. Stirring also reduces the retention time. Stirring therefore appears to be an attractive option for the system. No costs are quoted for the conversion of the treatment plant to a biogas power plant.

2. IMPLEMENTATION FACTORS: Not discussed.

3. ENVIRONMENTAL FACTORS: Treatment of the night soil results in a 68 percent death rate of parasite eggs. The percentage die-off is related to the retention time. Treatment, however, does not reduce the count of Colibacillus to a harmless level. Heating of the night soil to 60°C in an exchanger using waste heat from the generators results in 100 percent die-off of parasite eggs and a Colibacillus count of zero. Experiments on the heat treatment of night soil are still in progress.

The total nitrogen and total potassium content of the night soil does not change as a result of treatment in the digester. The content of ammonia nitrogen increases by 40 percent after digestion while the total phosphorus content declines by about one-half.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: Electricity Generation with Biogas, The Institute of Biogas, the Chinese Academy of Sciences, July, 1959.

Methane Generation from Human, Animal, and Agriculture Wastes, National Academy of Sciences, Washington, D.C., 1977.

5. OBJECTIVE OBSERVATIONS: No costs for the conversion of the treatment plant are quoted; maintenance and repair requirements and costs are not mentioned. No mention is made of cleaning of biogas prior to use in the engines.

6. SUBJECTIVE OBSERVATIONS: None.

ENTRY STATEMENT NO. 3

1. VIABILITY FACTORS: More than 500 biogas digestors of various designs using animal manure have been installed in Thailand. Most models are concrete wells (cylindrical or rectangular) with a capacity of about 3 to 8 cubic meters with floating steel gas holders. The main constraint to the expansion of the biogas program appears to be the high initial cost of the digesters of current designs.

Recently, the National Energy Administration has developed an alternative design which reduces initial cost and simplifies operation and maintenance. The alternative design uses common precast cement water jars. A typical plant includes two cement jars of 1.2 cubic meters each which serve as digesters and a separate gas holder. The latter is a metal cylinder with dome-shaped roof of about 0.5 cubic meter floating in a water tank. The latter is made of precast septic tank concrete casings. The gas holder is connected to the digester jars by plastic tubing.

The digesters are fed a mixture of 20 liters of cow manure and 20 liters of water per day and produce about 1 cubic meter of gas per day. This amount of gas meets the requirements of a family of 4 to 6 people. The retention time is 30 days. The average gas production rate is about 0.45 cubic meter of gas per cubic meter of reactor per day for an ambient temperature of 25°C. The production rate varies between about 0.3 and 0.6 cubic meter per cubic meter of reactor per day for temperatures ranging between 20°C and 30°C.

The estimated cost of the complete system is \$185 to \$200 or about \$90 to \$100 per cubic meter of digester capacity.

2. IMPLEMENTATION FACTORS: The modified design can be constructed by unskilled labor with materials readily available in rural areas. The digester can be installed above or below ground, is easy to clean if a bottom outlet is attached to the jars and can be expanded in modular fashion. These advantages as well as a cost affordable by rural families could provide the elements for expanding the biogas program in the country.

3. ENVIRONMENTAL FACTORS: The present emphasis in using biogas plants in the country is primarily the treatment of human wastes to reduce breeding of house flies and minimize the propagation of infectious deseases (Skrinde, 1981). No data concerning waste treatment characteristics or the use of sludge as fertilizer are quoted.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: Observations of Fuel Gas Productivity in Asia, R. T. Skrinde, in Fuel Gas Production from Biomass, Volume I, edited by D. L. Wise, CRC Press Inc., Boca Raton, FL., 1981.

5. OBJECTIVE OBSERVATIONS: The characteristics of the feedstock (volatile solids,. . .) and of the digested sludge are not provided. Actual maintenance and repair requirements and costs are not quoted. Modifications of the design to further reduce the cost (particularly of the gas holder) are under study.

6. SUBJECTIVE OBSERVATIONS: None.

ENTRY STATEMENT NO. 4

1. VIABILITY FACTORS: A fixed-cover, plug-flow, family-size digester has been operated since early 1981 in San Cristobal, Province of Imbabura, Ecuador (2,450 meters altitude). The digester is made of a semicylindrical concrete and brick foundation and of three 55-gallons drums cut in half as fixed cover. Except for the cover, the digester is underground. The volume of the digester, including the gas space, is 5.5 cubic meters. Gas is collected at the top of the fixed cover and stored in truck inner tubes. Weights can be used to compress the tubes and increase gas pressure. Manure from four cattle and two calves and latrine wastes from eight people are fed to the digester daily (60 to 100 kg daily). Retention time is 50 to 80 days. At the average ambient temperature of 17°C, the system produces 1.1 cubic meters of gas per day, or 0.2 cubic meter of gas per cubic meter of reactor per day; the design production rate is 1.8 cubic meters per day or 0.33 cubic meter gas per cubic meter reactor per day. Current production provides 4 to 5 hours of cooking per day which does not satisfy completely the needs of the family most of the time. Currently, storage capacity (0.8 cubic meter) is insufficient to collect all the gas produced. Effluent flows by gravity to the fields for fertilization.

The capital costs for the system are $450 ($82 per cubic meter of digester) for materials and $150 ($27 per cubic meter) for labor.

The major concern at present is the lack of storage capacity; degradation of the storage tubes and potential buildup of scum at the liquid-solid interface in the digester are longer term concerns.

2. IMPLEMENTATION FACTORS: The Government of Ecuador through the National Institute of Energy has initiated a research and development program on biogas generation including family-size to commercial-size digesters. A number of units of variable sizes and designs are tested around the country to determine the impact of site-specific conditions and of designs on digester performance. Experience gathered so far show that social concerns may hinder the development of biogas in poor rural areas. High initial costs and labor intensive operation and maintenance requirements are a major concern for family-size units. In cooperative or community situations, individual families are concerned about how their waste and labor contributions are measured and what share of the gas and effluent will be theirs. The distribution and equitable allocation of biogas to families located at a certain distance from the digester where gas pressure drops are difficult tasks.

3. ENVIRONMENTAL FACTORS: No systematic data concerning the potential environmental impacts of the technology (disease control, sludge as fertilizer, . . .) appear to be available at present.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: The demonstration program initited by the Government of Ecuador offers unique opportunities to collect valuable data on operating characteristics of different digester designs operating under a variety of site conditions. It appears to be the intention of the Government of Ecuador to collect these data in the future.

6. SUBJECTIVE OBSERVATIONS: If implemented and pursued successfully, the Ecuadorian demonstration program could provide a valuable data base which could benefit other developing countries.

ENTRY STATEMENT NO. 5

1. VIABILITY FACTORS: Various models of anaerobic digesters (biogas plants), available in India are reviewed with respect to their methods of construction and operation. They are developed by several local organizations and range in design sophistication from a simple batch digester to a large multidigester plant. The design features and operating data of these different digesters follow:

a. Batch Process Digester. This is a simple above-ground unit with circular shape, having two concentric plastered brick walls (clearance 12 to 15 cm or 4.8 in to 6 in). The gas holder is an inverted cylindrical tank made from 20-gauge galvanized steel, and it is about 2.8 m (8 ft) in diameter and about 1.8 m (6 ft) high. It is fitted to slide on four 2.54 cm (1 in I.D.) pipes. The pressure inside the gas holder is controlled by its own weight and the weight put on it. The overall dimensions of this unit are: 2.5 m x 1.8 m x 1.8 m (8.2 ft x 6 ft x 6 ft). It is filled with waste vegetable material, slaughter house waste, other cellulose wastes and cow manure to 30 cm (1 ft) below the top. Enough water is added to keep the solid mass in a dilute slurry. Gas production starts after a week, with the rate of production 3.4 m^3 (120 ft^3) of gas per day for 30 to 40 consecutive days and dropping to about 2.5 m^3 (90 ft^3) after 40 days. About every two months, the old charge is replaced with fresh feedstock, producing roughly 3.6 tonnes (4.0 tons) of solid residue.

b. Continuous Biogas Plant. This is the most common unit used in the rural areas of India. It is built underground. A hole about 5.5 m (18 ft) deep and 3.6 m (11.8 ft) wide is dug. A concrete base is constructed on top of which the digester is built. The inner walls of the digester are constructed, using a mixture of one part of cement, two parts of sand, and eight parts of limestone, and they extend about 1.2 m (4 ft) above ground. The feed mixing tank and the effluent holding tanks are placed on opposite ends of the digester and connected to the digester by inlet and outlet pipes, respectively. The floor of the feed-mixing tank is kept above the ground level to supply the necessary hydraulic head for feeding the plant. The feed is a dilute slurry of cow manure. Approximately 50 kg (110 lb) of cow manure is required to produce about 3.0 m^3 (100 ft^3) of biogas per day. The gas holder is an inverted cylindrical drum, 1.5 m (5 ft) in diameter and 1.2 (4 ft) high, fabricated of 12-gauge M.S. sheet iron and guided by an iron pipe which is fixed at the center of the digester by a support structure.

The major advantages of this type of digester are: the weight of the metal gasholder provides a constant gas pressure of the order of 10 cm of water, and as the feedstock is usually diluted to less than 10 percent solids, sludge formation is slow and frequent cleaning is not necessary. Tests conducted in India suggest that maximum gas production rate, 0.45 cubic meter per cubic meter of digester per day is reached for a total solids percentage of about 9.5 percent in the influent, which for the feedstocks used corresponds to a percentage of about 7.2 percent of volatile solids in the influent. Under those conditions, the gas production rate corresponds to about 0.14 cubic meter of gas per kilo of volatile solids added per day.

The Indian digester, however, has some disadvantages: the steel gas holder is expensive; serious corrosion problems occur with the gas holder; the uninsulated metal gas holder is a good conductor of heat and is not well suited for cold climates, and the plant has little capacity for digesting fibrous plant material.

The cost of a 12 cubic meter digester capable of producing an average of about 3 cubic meters of gas per day is estimated at about $425 or about $35 per cubic meter of digester. Economies of scale are possible for larger systems. For example the cost reported for a 38-cubic meter digester producing an average of 10 cubic meters of gas per day is about $15 per cubic meter of digester;

the cost of a 400-cubic meter digester producing an average of 60 cubic meter of gas per day is about $9.2 per cubic meter.

c. Large-scale Digester Plants. Large-scale plants are constructed to have a gas capacity of 28 m^3 to 84 m^3 of gas per day (1,000 to 3,000 ft^3 of gas per day) which is calculated on the basis of 1 m^3 of material giving 1 m^3 of gas per day. Generally, these large-scale plants include multiple digesters with a common feed-mixing tank and a gas holder. Unlike small digester plants, the gas holders are fixed structures. Large biogas plants are uncommon in India; they are being tested in some rural communities for supplying gas and electric power for at least 50 houses.

2. IMPLEMENTATION FACTORS: The family-size (1.7 m^3 or 60 ft^3 of gas per day) biogas digester plants are not within the reach of poor people in Indian villages. Even if a large portion of the cost of the digester is provided through a government subsidy, bank loan, etc., the feedstock supply requires at least four animals per family. It is estimated that typically only 5 percent of the people in Indian villages own four or more animals.

Biogas is used for cooking and lighting in rural areas. Cooking burners can be manufactured in rural metal shops. Biogas is also used in gasoline or diesel driven internal combustion engines. Diesel engines are often run as dual-fuel engines in which about 10 percent of the fuel used is diesel fuel. Engines rated between 1 and 10 horsepower require about 0.45 cubic meter of biogas per horsepower-hour.

3. ENVIRONMENTAL FACTORS: The nitrogen content of digester sludge is about 0.75 percent higher than that of the same feedstock (cow manure) after composting. The increased fertilizer value of digester sludge has been confirmed by significant increases in crop yields. Much emphasis is placed on improving the methods of handling digester sludge. The use of biogas for cooking has also resulted in some social benefits such as reduced eye irritation due to smoke from cooking stoves, reduced time spent in preparing cow dung cakes for cooking, etc.

4. RELATED PAPERS AND SUGGESTER FURTHER READING:

Design Analysis of Small-Scale Anerobic Digesters in India, Energy from Biomass and Wastes, C. Chiranldvi, Institute of Gas Technology, September 1978, pp. 449-485.

Bioenergy Systems Reports, March 1982: Biogas in Developing Countries, Ed. D. B. Mahin, available through USAID missions in Developing Countries.

Biogas Production from Animal Manure, Biomass Energy Institute Inc., 304-870 Cambridge Street, Winnipeg, Manitoba, Canada, March 1978.

Observations of Fuel Gas Production in Asia, R. T. Skrinde, in Fuel Gas Production from Biomass, Volume I, Ed. D. L. Wise, CRC Press Inc., Boca Raton, FL., 1981.

5. OBJECTIVE OBSERVATIONS: The report by Sathianathan contains more practical information on biogas systems than can be reported here; the report should be consulted by groups interested in pursuing the development of Indian-type digesters.

6. SUBJECTIVE OBSERVATIONS: No relevant observations.

ENTRY STATEMENT NO. 6

1. VIABILITY FACTORS: The objective of the system installed at the State Reformatory Farm near Monroe, WA., USA, was to design and operate a full-scale digester using dairy cow manure feedstock. Wastes from about 200 cows are treated in the system. The system has run continuously since August 1977. Original funding was provided by the Washington State Department of Ecology; further funding was then provided by the U.S. Energy Research and Development Administration (now Department of Energy).

The system is a complete mix reactor using the state-of-the-art design for municipal sewage treatment plants. Manure containing some sawdust and wood chips bedding is collected daily in the barn and mixed with water in an influent mixing tank of 8.9 cubic meters. The influent mixing pump capacity is 7.5 kW. About 2,000 kg of manure are mixed with about 18,600 kg of water. The input solids concentration is 10 weight percent; volatile solids concentration is 5.8 kg per cubic meter of digester and total solids concentration is 10.9 kg per cubic meter of digester. The digester tank is a standard manure storage tank with an air tight silo roof capable of holding a pressure of 4.9 kPa (0.7 psi). The roof of the tank is insulated with about 9 cm of polyurethane foam (R-12) and the exterior walls are insulated with 10 cm of styrofoam. The volume of the digester is 189 cubic meters. The digester is heated to 35°C by circulating hot water provided either by an auxiliary boiler of 396 MJ per hour capacity or by the coolant system of the internal combustion engine burning biogas to produce electricity. The digester was designed to be continuously mixed by gas recirculation. Experience, however, showed that sufficient natural mixing occurred because of gas movement and natural convection; the use of the gas recirculator was therefore discontinued. The solids concentration in the digester is 8.2 weight percent. Volatile solids are reduced by 34 percent for a retention time of 12 days. The biogas production rate is 0.237 cubic meters per kilo of volatile solids fed to the system. Two hundred and thirty cubic meters of gas with a heating value of 22.5 MJ per cubic meter (about 600 Btu per cubic foot) are produced daily. About 80 cubic meters of gas are used daily to maintain the temperature of the digester. After removal of hydrogen sulfide, the gas is compressed to 1.65 MPa (240 psi) by a two-stage 1.5 kW compressor and stored in three tanks having a total capacity of 186 cubic meters. The excess gas, if any, is vented or flared. The gas can be used either to produce process hot water or steam for the dairy farm operations or to run an internal combustion engine-generator set supplying emergency electricity. The generator has a peak capacity of 40 KVA. The conversion efficiency for electricity generation is 15 percent for a 20 kW load. The digested manure flows by gravity to a storage lagoon where it is kept until it is applied to the fields.

The quantity of gas needed to maintain the temperature of the digester ranges from about 70 cubic meters per day in June and July to about 100 cubic meters per day in February and March. On a yearly basis, heating of the digester consumes about 44 percent of the gas generated.

Some operational problems due the high moisture level of the gas were encountered, i.e., line clogging and freezing caused by condensation. They were handled by pipe insulation and water traps. The engine used to produce electricity was originally a natural gas engine; the use of biogas resulted in a loss of capacity of about 37 percent.

The capital cost for the system is estimated at $61,000 for a packaged system without engine-generator set; with the generator, the cost is estimated to be $65,000. The system requires about one man-day per day for operation and maintenance; maintenance and repair costs are estimated to be about $1,000 per year. The estimated cost of the gas (about $5.20 per GJ) and electricity (0.054 per kWh) is competitive with current cost of energy in some areas of the country. These costs do not include a credit for the fertilizer value of the sludge.

2. - IMPLEMENTATION FACTORS: The system described uses fairly sophisticated technology originally designed for waste water treatment. Operation of the system showed that careful monitoring of the system was required for successful performance. Untrained farmers therefore may not be able to maintain performance at its highest level. Operation of the system also showed that operating conditions could be modified with respect to those accepted for waste water treatment; this offers the opportunity to simplify the design to reduce cost and simplify operations.

3. ENVIRONMENTAL FACTORS: Although not explicitely discussed, the system presumably abides by the standards for waste treatment set by the Environmental Protection Agency.

4. RELATED PAPERS AND SUGGESTED FURTHER READINGS: Engineering Feasibility of Fuels from Biomass Utilizing Dairy Farm Residue, R. T. Skrinde, J. J. Fritz, and R. W. Seabloom, in Fuel Gas Production from Biomass, Volume II, edited by D. L. Wise, CRC Press, Inc., Boca Raton, FL, 1981.

Operation of a Dairy Farm Digester Using Available Equipment and Technology, E. Coppinger, D. Baylon J. Lenart, in Fuel Gas Production from Biomass, Volume I, edited by D. L. Wise, CRC Press Inc., Boca Raton, FL, 1981.

5. OBJECTIVE OBSERVATIONS: This design is probably too costly and too complex for wide-scale application in developing countries. The data and exprience collected while operating the system however, provide a good data base for the design and implementation of practical systems in other contexts.

6. SUBJECTIVE OBSERVATIONS: None.

DIRECT COMBUSTION

Detailed data on direct combustion technology are presented in:

Direct Combustion Systems to Product Power from Biomass: A State-of-the-Art Review, USAID Office of Energy, Washington, D.C. (in preparation).

Selected data on direct combustion technology are presented in the entry statements in this section. The entry statement index, Table C-III, is designed to aid readers in their search for specific data entries. The location of entry statements and the corresponding literature sources are indicated in Table C-IV.

TABLE C-III

ENTRY STATEMENT INDEX FOR DIRECT COMBUSTION

Source of Data (Country):	Entry Number:
Hawaii	1
United States (continental)	2, 3, 4
West Germany	5
Data Type:	
Commercial Systems:	
- Small/Medium	2
- Large	1, 3, 5
Pilot/Demonstration	4
Biomass Feedstocks:	
Wood and wood wastes	2, 3, 4, 5
Agricultural wastes	1

TABLE C-IV

SOURCE AND LOCATION OF ENTRY STATEMENTS

Entry Statement Number and Page		Literature Source
1	C-203	"Power Generated from Sugarcane Residues Supplies 20 percent of Electrical Demand on the Island of Hawaii," in Biomass Energy Success Stories, Report prepared for the U.S. Department of Energy, Contract No. EG-77-X-10-0285, Biomass Energy Institute, Washington, D.C., March 1978.
		Private Communications - Biomass Energy Intitute.
2	C-204	"Textile Mill Derives steam for Bleaching and Dyeing Operations from a Wood-Fired Boiler Plant," in Biomass Energy Success Stories, ibid.
		"Wood Residue - An Alternate Source of Energy", J. Scott, Alabama Forest Products, Vol. 20, No. 1, January 1977, pp 6-9.
3	C-205	"Wood Residues Produce Steam for Central Heating and Electric Power," in Biomass Energy Success Stories, ibid.
		"Energy Generation from Wood-Wastes" O. D. Brown, paper presented to the International District Heating Association, French Lick, Indiana, June 20, 1973.
4.	C-206	"Small Institutional Heating Plant Utilizes Chipped Forest Residues Fuels," in Biomass Energy Success Stories, ibid.
		"Development of a Small Institutional Heating Plant to Utilize Forest Residue Fuels", J. G. Riley, American Society of Agricultural Engineers, Paper No. NA76-101, 1976.
5	C-207	"Wood-Fueled Power Plant Heats Debate in Germany" H. R. Frazer, in World Wood - The International Forests Products Magazine, Industrial Focus: Industrial Wood Energy, Volume 23, No. 1, pp 14-15, February 1982.

ENTRY STATEMENT NO. 1

1. VIABILITY FACTORS: The Pepeekeo Mill of the Hilo Coast Processing Company on the island of Hawaii uses bagasse and residual leaf trash to fire a large steam boiler producing 330,000 pounds of steam (about 150,000 kilos of steam) per hour at 1,200 psi (about 80 atmospheres or about 8,300 kPa). The high temperature steam from the boiler passes through three successive processes which extract energy from the steam at successively lower temperatures. In the first step, the high pressure, high temperature steam enters a 35,000 horsepower turbine connected to a 28 megawatt generator. The electricity produced is sold to the Hawaiian Electric Light Company under a 20-year agreement; the mill sells about 100 million kWh of electricity per year to the power company. This amount of electricity supplies about 20 percent of the island's demand for electricity. In the second step of the conversion process, the exhaust steam from the turbine (150 psi, about 10 atmospheres or about 1,030 kPa) drives three low-pressure turbines to generate mechanical power for the mill. Finally, in the third step of the conversion process, the exhaust from the three low-pressure turbines supplies heat to a series of evaporators used in the conversion of cane juice to raw sugar. At this point, most of the energy from the steam has been extracted and the condensed steam is returned to the boiler as feedwater. The arrangement described here is a good example of cogeneration, i.e., simultaneous production of mechanical/electrical power and of process heat (see "Steam Turbines" in Section B of this Handbook). No costs for construction, operation, and maintenance of the plant are quoted.

The plant has operated successfully for over 6 years. In 1977, the purchase price of electricity was 20 mills ($0.02) per kWh which resulted in a yearly revenue of about $2 million from the sale of electricity.

2. IMPLEMENTATION FACTORS: In 1976, a shortage of bagasse resulted in the need to use supplemental raw energy to maintain the plant in operation and insure the commitments of electricity made to the power company. A substantial fraction of this supplemental energy was supplied by fuel oil, and the balance was supplied by wood chips purchased from a neighboring planing mill. The prices of these supplementary resources were $12.15 per barrel and $9 per ton. This problem of long-term availability of biomass feedstocks can be particularly crucial for large scale conversion plants. Long-term planning of feedstock supplies and provisions for substitute feedstocks are important elements to consider in planning studies for large-scale projects.

3. ENVIRONMENTAL FACTORS: The development of the power plant was stimulated by a need for improved environmental control techniques particularly to reduce the discharge of residues from the plant to the ocean.

Although no mention of specific environmental control measure are made in relation to the plant discussed, a related paper (see 4 below) indicated that in a similar case of bagasse-fired boilers, special equipment had to be installed to reduce particulate stack emissions.

4. RELATED PAPERS AND SUGGESTED READING: "Biomass Energy Success Stories," Report prepared for the U.S. Department of Energy, Division of Solar Technology, Contract No. EG-77-X-10-0285, Biomass Energy Intitute, Inc., Washington, D.C., March 1978.

5. OBJECTIVE OBSERVATIONS: Economic data should be gathered and analyzed to evaluate the feasibility of the plant under different sets of market/economic conditions.

6. SUBJECTIVE OBSERVATIONS: The attractiveness of bagasse as energy feedstock will depend on site/country conditions. For example, the case of

a large-scale sugar mill was observed in Ecuador where only part of the bagasse is used to generate electricity; the other part is sold as raw material for the manufacture of industrial paper bags. In this case, the higher value of bagasse as raw material justifies the purchase of supplementary fuel oil to provide part of the energy of the sugar mill. In another case observed, bagasse was both an energy feedstock and sold as animal feed. These potential trade-offs will have to be carefully examined on a case-by-case basis before launching biomass energy projects.

ENTRY STATEMENT NO. 2

1. VIABILITY FACTORS: A large textile mill in Alexander City, Alabama, was converted from natural gas and fuel oil to wood as its source of energy to generate the steam needed by the dyeing and bleaching operations. Coal was considered as an alternative fuel but rejected in view of the high cost of the pollution control equipment required by this fuel.

Two 27,000 kg per hour (60,000 pounds per hour) steam boilers are fired with sawmill residues (mostly wood chips) collected from about 30 sawmills scattered throughout the surrounding area. The residues are fed to the boilers at a rate of about 18 metric tons per hour. The biomass fuel replaces about 6 million gallons (about 23 million liters) of oil on an annual basis. Based on 1976 fuel oil prices, it is estimated that the system will pay for itself in about 5 years. The system has operated satisfactorily since 1976.

2. IMPLEMENTATION FACTORS: One of the most significant feature of the system described is the complex logistical problem of supplying the plant with wood residues on a continuous basis. Wood residues are collected from 30 sawmills scattered in the area and hauled by trailer trucks on a 24-hour basis to insure a delivery rate of about 2,700 metric tons (3,000 tons) per week. The feedstock delivered at the plant is screened, and the large pieces are shredded before being transferred to a storage pile maintaining a 1 week supply of fuel. The wood chips are conveyed directly to the furnace as required.

3. ENVIRONMENTAL FACTORS: Before they sold their residues to the textile mill, the sawmills disposed of their residues through burning in teepees. The sawmills were under considerable pressure from the Environmental Protection Agency to curtail this practice. Now, this high nuisance residue is profitably

sold to the textile mill which disposes of it in a usefull and apparently environmentally acceptable manner.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: "An Evaluation of Wood Waste Energy Conversion Systems," B. H. Levelton, Western Forest Products Laboratories, 6620 N.W. Marine Drive, Vancouver, B.C., Canada, V6T 1X2, 1978.

5. OBJECTIVE OBSERVATIONS: Economic data (capital and maintenance and repair costs) should be gathered and analyzed to evaluate the potential of the system in different economic and market conditions.

6. SUBJECTIVE OBSERVATIONS: None.

ENTRY STATEMENT NO. 3

1. VIABILITY FACTORS: The Eugene Water and Electric Board provides water, steam and electric services to the Eugene, Oregon, metropolitan area. Electricity is provided by three hydro-electric plants of 128-megawatt capacity and by a steam-electric plant of 33.8 megawatt capacity. The steam plant is fueled with surplus forest residues gathered in the surrounding area. The steam plant also provides steam-heating service to an area of about 5 square kilometers (2 square miles) comprising a business district, a hospital, a college campus, a cannery, and a 6.5-hectare (16 acre) greenhouse complex.

Hogged wood residues consisting mostly of bark are gathered in nearby wood product mills and delivered to an outdoor storage pile at the power plant. The fuel is fed to two boilers through a handling system, which includes sizing screens, pulverizers, conveyer belts, and metal detectors. A third oil-fired boiler is available as standby. The combined steam-generating capacity of the three boilers is 204,000 kilos of steam per hour (450,000 pounds of steam per hour). The boilers are matched to turbine-generator units of 6.0, 7.5, and 11.5 megawatt capacity. Under normal conditions, the steam boilers are operated year round. During 4 months of the year, the plant is on standby for electric power generation, during the remainder of the year, the balance of the steam capacity is used to generate electricity.

Steam for the heating utility amounts to about 227 million kilos per year (500 million pounds per year). The corresponding fuel requirements are about 340 thousand cubic meter of residues (12 million cubic feet) per year. At a cost of about $0.90 per cubic meter for residues, the cost of fuel per year amounts to about $300,000 per year. The equivalent cost of oil — 180,000 barrels at $12 per barrel — would be $2.16 million.

2. IMPLEMENTATION FACTORS: Wood residues are the principal fuel for the plant. However, coal and oil are available for standby duty. Coal is used on occasions in conjunction with wet-wood fuel to assist combustion. No mention is made of logistical problems in providing the wood fuel.

The plant was assembled between 1931 and 1951 period and apparently works satisfactorily.

3. ENVIRONMENTAL FACTORS: Utilization of the wood residues by the electric utility has contributed to resolving the problem of disposal of wood residues in the Eugene area and has reduced air pollution.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: "Large Bark and Wood Waste Fired Boiler: A Case History" W. M. Nanney and F. C. Gustafson, Technical Association of the Pulp and Paper Industry, TAPPI Conference Papers, pp 19-25, Atlanta, GA., 1976.

5. OBJECTIVE OBSERVATIONS: Analysis of historical cost data would be very valuable in estimating the potential of the technology in different market/site conditions.

6. SUBJECTIVE OBSERVATIONS: None.

ENTRY STATEMENT NO. 4

1. VIABILITY FACTORS: The Agricultural Engineering Department of the University of Maine has developed a small, fully automated heating system suitable for small institutional and/or commercial buildings. The unit currently in operation at the university has a capacity of about 211,000 kJ per hour (200,000 Btu or about 50,000 kcal) and maintains a temperature of 70°C in the 560 square meter (6,000 square feet) Agricultural Machinery Building.

The unit comprises a 1 cubic meter firebox, a 21-cubic meter storage bin and several heat exchangers designed to maximize the overall heat recovery. The unit burns chipped logging residues having a bulk density of 240 kilos per cubic meter (15 pounds per cubic foot) at a maximum rate of about 14 kilos per hour (30 pounds per hour). The fuel reserve in the storage bin is sufficient for approximately 3 weeks of operation. The fuel is fed to the furnace by a motor-driven, screw-type conveyor. Exhaust gases from the firebox first pass through a heat exchanger, which warms incoming air and return room air for heating. Hot air to the building can be circulated at a rate of about 85 cubic meters per minute (3,000 cubic feet per minute). Exhaust gases then pass through a drier which reduces the moisture content of the woodchips fed to the firebox. Finally, the exhaust gases are circulated though a condenser unit, which receives heat from the moist flue gases to preheat incoming air. The overall efficiency of the unit is quoted as 90 percent. Wood chips fuel costs $15 per dry ton (1978 prices) and the oil-equivalent value of the wood fuel is $40 for oil costing $0.12 per liter ($0.43 per gallon). No costs are quoted for the unit.

2. IMPLEMENTABILITY FACTORS: No details are given concerning particular operational problems except that the unit appears to have operated successfully since its installation (around

1978). Prior to the installation of this unit, the same group had designed and successfully tested a smaller wood chip furnace for residential heating applications.

3. ENVIRONMENTAL FACTORS: No problems are mentioned.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: Cost and operational performance data would be most valuable.

6. SUBJECTIVE OBSERVATIONS None.

ENTRY STATEMENT NO. 5

1. VIABILITY FACTORS: A timber processing plant including a sawmill and impregnation plant at Bingen-Gaulsheim, West Germany, has recently (about 1980) installed a wood-fired cogeneration unit of 10.5 million kWh per year capacity.

The plant generates from 30,000 to 34,000 tons per year or 140 to 150 tons per day of wastes including slabs, trim wastes, sawdust, and bark. Wastes also include noxious phenolic condensates from the creosote impregnation operation. The plant comprises two compact water-tube boilers capable of burning 6 tons per hour of waste wood to produce 8.5 ton of steam per hour at 26 kg per square centimeter pressure. The furnace heat is transferred by radiation to the water tubes, arranged in a rectangular cage. Oil burners are provided for emergency operation. The burners are also used to burn off the phenolic condensates. The steam from both boilers first passes through a high pressure single-stage turbogenerator unit. This unit works as a back-pressure unit reducing the steam pressure from 26 kg/cm^2 (bar) to 6 kg/cm^2. Exhaust steam at 310°C is used for process steam and to feed the second turbine. The latter is a condensing turbine reducing pressure from 6 kg/cm^2 to 0.25 kg/cm^2. The combined capacity of the two turbines is 2,400 kW. Based on an average calorific value of 2,400 kcal per kg of wood, the total annual capacity of the unit is 10.5 kWh per year. The mill electrical demand is about 4.5 million kWh per year with a further 1 million kWh reserved for future expansions. The original plans called for the sale of the extra electricity produced to the grid. At full capacity the plant can save an estimated 9,000 tons of bunker fuel oil per year. The cost of the power plant itself is about $1.75 million, or about $730,000 per megawatt installed ($730 per kW installed). Modifications to the original plant to utilize the process heat and electrical power generated amounted to another $1.75 million.

2. **IMPLEMENTATION FACTORS:** The original plans called for the sale of the surplus electricity to the local grid. However, although electrical power charges were $0.071 per kWh in 1979, resale tariffs offered never reached more than $0.018 per kWh. As a result, the company never ran the plant at more than 50 percent capacity, enough to satisfy its internal demand. The excess wood wastes are sold as firewood. Negotiations are under way to increase the resale value of the excess power generated. The plant has operated satisfactorily for over two years.

3. **ENVIRONMENTAL FACTORS:** A first factor in determining the viability of the power plant was the desire to reduce escalating energy costs. Another significant factor in determining the viability of the plant was the escalating cost of disposal of the wastes, both wood wastes and chemical wastes from the impregnation plant. Both types of wastes are currently burned in the boilers with no environmental problems reported.

4. **RELATED PAPRS AND SUGGESTED FURTHER READING:** "Cogeneration - How to Get Double Duty From Energy", A. Orr, in World Wood - Industrial Wood Energy, pp 16, 17, February 1982.

5. **OBJECTIVE OBSERVATIONS:** None.

6. **SUBJECTIVE OBSERVATIONS:** None.

SMALL-SCALE GASIFICATON

Detailed data on small-scale gasification technology are presented in:

Gasification: A State-of-the-Art Review. U.S.A.I.D. Office of Energy, Washington, D.C. (in preparation).

Selected data on small-scale gasification technology are presented in the entry statements in this section. The entry statement index, Table C-V, is designed to aid the readers in their search for specific data entries. The location of entry statements and the corresponding literature sources are indicated in Table C-VI.

TABLE C-V

ENTRY STATEMENT INDEX FOR SMALL-SCALE GASIFICATION

Source of Data (Countries):	Entry Number:
Sweden	1
New Zealand	2
Philippines	3, 4
Data Type	
Pilot/Demonstration	4
Commercial systems	
- Small	1, 2, 3
- Large	—
Biomass Feedstocks:	
Wood and wood waste	1, 2, 3
Agricultural Residues	4

TABLE C-VI

SOURCE AND LOCATION OF ENTRY STATEMENTS

Entry Statement Number and Page		Literature Source
1	C-303	"Generator Gas: The Swedish Experience from 1939 to 1945," Translated by the Solar Energy Research Institute, SERI/SP-33-140, Golden, CO., 1979.
2	C-305	"Gas Producers for Motor Vehicles: A historical Review," M. L. Bailey, Report No. C.D. 2279, Department of Scientific and Industrial Research, Chemistry Division, New Zealand, February 1979.
3	C-306	"A Handbook on Gasifier Technology: the Philippine Experience," Gasifier and Equipment Manufacturing Corporation, Chipeco Building, Shaw Blvd, Pasig, Metro Manila, Philippines, 1981.
4	C-307	"Producer Gas as Fuel for Diesel Engines," Ibarra E. Cruz, College of Engineering, University of the Philippines, October 1976.

ENTRY STATEMENT NO. 1

1. VIABILITY FACTORS: Liquid fuel shortages during World War II resulted in large-scale commercialization of gasifiers in Sweden. Between mid-1940 and late 1941, the number of gasifiers used for automotive applications raised from about 3,000 to about 72,000. This amounted to the conversion of about 35 percent of the total fleet of private cars, buses, and trucks to gasifiers.

The two raw materials considered for gasifier fuel were wood and peat. Peat generally has a high content of fusible ash, which reduces its attractiveness as fuel for gasification. After semidrying, machine-extracted pieces of peat are cut into smaller pieces (briquetted) before use in gasifiers. Peat can also be converted to peat coke. Gasifier fuel was mostly derived from wood, i.e., processed wood or charcoal. Wood was processed into blocks, billets, and chips of appropriate size or converted to charcoal. Wood charcoal was more commonly used than processed wood.

The gasifiers were generally of the downdraft type. In some models, water vapor could be injected through the air inlet to increase the fuel value of the producer gas (higher H_2 and CO content). Several models of various degrees of sophistication and adapted to various qualities of charcoal (fine charcoal, blocks, or briquettes) were manufactured at the time. Similarly, several models of downdraft wood gasifiers were available, including a model suitable for wood, brown coal, and peat. Private-car gasifiers had a fuel container of 1.5 hectoliters for charcoal and of 1 to 2 hectoliters for wood. Wood gasifiers for trucks had a fuel container of 2 to 3 hectoliters, and 3 to 6 hectoliters for buses.

Gas must be cleaned before use in an engine to reduce the content of tar, dust particles, and water. Various systems are used - cyclones, filters, condensers, etc. - generally in combination to obtain a gas of suitable quality.

The gas composition is approximately as follows: CO_2: 11 percent, O_2: 0.1 percent,, CO: 19 percent, H_2: 18.8 percent, N_2: 50.2 percent, others: 0.9 percent. The effective heating value of producer gas obtained from charcoal ranges between 1,100 and 1,350 kcal per normal cubic meter (133 to 163 Btu per standard cubic foot). For gas obtained from wood, the heating value ranges from 1,200 to 1,400 kcal per normal cubic meter (145 to 170 Btu per standard cubic foot). The following approximate fuel consumptions were recorded: wood (about 4,500 kcal/kg): 1 kg per hp-h; charcoal (about 7,900 kcal/kg): 0.550 kg per hp-h; gasoline (about 10,500 kcal/kg): 0.275 kg per hp-h. Gas production rates were as follows: 1 kg of wood gives about 2.2 normal cubic meters of producer gas at 1,300 kcal per normal cubic meter; 1 kg of charcoal gives about 4 normal cubic meters of producer gas at 1,300 kcal per normal cubic meter. Taking into account the increased driving in low gear with producer gas compared with gasoline, fuel consumption during idle, firing, and starting of the gasifier, etc., it has been estimated that 1 liter of gasoline corresponds to approximately 3 kg of wood or 1.65 kg of charcoal during practical operation. When comparing various fuels, it is also important to take into account the amount of raw materials used in their production. One cubic meter of raw wood will provide about 80 kg of charcoal or 375 kg of wood fuel. Therefore, the raw material consumption for charcoal will be about 2.5 times higher than for operation of the gasifiers with wood.

Gasoline internal combustion engines can be fairly easily converted to use of producer gas. During producer gas operation, power losses of 45 to 50 percent compared with gasoline operation were recorded. Diesel engines were converted to producer gas use by installing a spark ignition system on the engine. Operation on producer gas resulted in a power loss of about 20 percent compared with operation with diesel fuel. The cost of gasifiers for automotive applications is estimated at about $100 per kW.

2. IMPLEMENTATION FACTORS: In the early 1940's the Swedish Government established the Swedish Generator Gas Company to promote the production and distribution of gasifiers for transportation, farm, and fishing applications. The implementation of a large-scale program such as the one existing in Sweden at the time requires careful planning of the utilization of the feedstock resources, i.e., the forest resources in the present case. An adequate balance must be found between consumption of the resources for energy and consumption of the resources for other, more traditional, uses to avoid indiscriminate utilization of the forest resources. This is particularly crucial when charcoal is the fuel used in gasifiers because charcoal consumes about 2.5 times more raw forest resources than wood fuel for gasification. A national program must also provide for the distribution of the gasification fuels. In Sweden, this was done through service stations selling gasifier fuel supplied by large processors.

3. ENVIRONMENTAL FACTORS: Operation of gasifiers involves serious problems such as toxic hazards, fire hazards, and traffic hazards. Toxic hazards involve mostly carbon monoxide poisoning. Government agencies imposed strict safety measures including requirements for improving the quality and installation of gasifiers and promoted education programs on the operation and maintenance of gasifiers. Most gasifier-related fires occurred during startup in garage or parking areas. Safety recommendations were issued by government agencies in collaboration with insurance companies, which reduced the number of fire related accidents. An increase in traffic accidents (normalized to the number of cars in circulation) was recorded during the period of intensive use of gasifiers. This increase was probably related to changes in vehicle performance (lesser acceleration for instance), attempts by drivers to compensate for changes in performance (acceleration before hills, etc.) and impairment of driver's reactions due to low-level poisoning by carbon monoxide in the cab.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: "Producer Gas 1980 - Local Electricity Generation From Wood and Agricultural Residues," B. Kjellstrom, Report sponsored by the International Foundation for Science and the Beijer Institute, Stockholm, Sweden, June 1981.

"State-of-the-Art for Small Scale Gas Producer - Engine Systems," A. Kaupp and J. R. Goss, Final report to USDA - Forest Service, Contract No. 53-319R-0-141, March 1981, (reference section).

5. OBJECTIVE OBSERVATIONS: The Swedish report describes all important aspects of small gasifiers and provides a valuable background on the implementation of a national gasification program. Planning aspects (resources, regulations, safety, etc.) are well documented.

6. SUBJECTIVE OBSERVATIONS: None.

ENTRY STATEMENT NO. 2

1. VIABILITY FACTORS: During World War II, New Zealand had a limited gasifier program. In 1943, about 1,800 cars and about 500 trucks were operating on gasifiers. A government technical committee tested various designs of gasifiers and prepared drawings and specifications for commercial units. A brochure on charcoal manufacture and an operating manual were also prepared.

The unit recommended by the technical committee was designed to be manufactured from available materials, to be low cost, to be easy to manufacture, to start quickly, and to produce a gas of good quality. The gasifier is an updraft system with no water injection. The shell has no refractory liner (the walls are protected against overheating by a layer of fuel) and air is introduced through a tuyere at relatively high velocity to facilitate idling and improve gas supply during periods of high gas demand. The gas is cooled through a system of pipes and then cleaned through a cyclone separator and dry filter (oiled coke, sawdust, fiber, etc.). Charcoal was the recommended fuel and was sold in retail outlets. The major disadvantage of charcoal is its bulkiness; the latter could be reduced by briquetting the charcoal.

Maintenance of the unit was estimated to require about one-half hour every 100 miles (160 km) for filling the fuel container, removing ash and clinker, cleaning the filters, etc. Performance on producer gas was lower than on gasoline particularly for acceleration and climbing hills. The power loss was estimated to be about 50 percent of a comparable engine running on gasoline. Increased engine wear due to abrasive dust and corrosive compounds was recorded when using gasifiers.

The calorific value of gas produced in an updraft unit using charcoal as fuel ranged between 1,100 kcal per normal cubic meter for a unit without water added to 1,400 kcal per normal cubic meter for a unit with water injection. Comparable values were 1,100 to 1,200 kcal per normal cubic meter for coke-fired units.

Equivalent fuel consumptions were about 1.5 kg of charcoal, 1 kg of briquettes and 1.4 kg of coal per liter of gasoline. A rule of thumb was about 0.5 kg of fuel per hp-h for trucks.

The estimated cost is $50 to $100 per kW for units of about 30 hp (this cost is a 1940 cost adjusted for 5 to 7 percent inflation over a 42-year period; this quote should be used with extreme caution).

2. IMPLEMENTATION FACTORS: The government of New Zealand provided complete specifications for the manufacture of gasifiers including gas-cleaning equipment and a retrofit procedure for existing gasoline engines. Consideration was also given to the production of the recommended fuel, charcoal. This careful planning effort did not result in an extensive adoption of the system, partly because gasoline shortages may not have been as critical as expected, but also, apparently, because of the relatively high cost of the system for private users. Under conditions prevailing at the time, however, gasifier-retrofitted engines were cheaper to run than gasoline engines.

3. ENVIRONMENTAL FACTORS: Exhaust gases from gasifier-operated engines contain less CO (0.5 percent) than gasoline-operated engines (0.6 to 10.5 percent) but more CO_2 (17.3 percent vs 7.8 to 12 percent). The gasifier-operated engines also released nitric oxides. Cleaning of the gasifiers is required fairly often, in some cases as often as every 35 miles. As a result, heaps of ash and clinker were occasionally found along the roads.

4. RELATED PAPERS AND SUGGESTED FUTHER READING: "Producer Gas from Charcoal for a Low Output Power System," G. R. Breag, A. P. Harker,

A. C. Hollingdale and D. Pearce, Tropical Products Institute, Culham, Abingdon, Oxon, U.K., paper presented at the International Solar Energy Society Congress, Brighton, August 1981.

"The Economics of Small Producer Gas-Engine Systems," P. Rogers, Department of Applied Mechanics at IIT-Delhi, New Delhi, August 1981.

5. OBJECTIVE OBSERVATONS: The report contains essential information concerning the gasifier experiment in New Zealand including useful design drawings and operation instructions.

6. SUBJECTIVE OBSERVATIONS: None.

ENTRY STATEMENT NO. 3

1. VIABILITY FACTORS: Gasifier technology was revived in the Philippines in 1967. Various government agencies and institutions investigated the use of gasifiers for irrigation and transportation applications. In mid-1979, five diesel engine-driven pumps were retrofitted to producer gas to test gasifiers for irrigation applications. In 1980, 25 gasoline engine vehicles and three diesel vehicles using charcoal fueled gasifiers were tested extensively in a 2,500-kilometer road endurance test.

Several types of gasifiers were investigated. Downdraft models fired with charcoal were used for stationary applications (irrigation, power generation). An updraft model using charcoal and steam was designed for vehicular applications. The gas has a slightly higher energy content because of higher H_2 content but is less clean than the gas produced by the downdraft system. A third model, Dendrogas, is a downdraft system fueled with wood chips; the moisture in the chips results in higher energy content with a cleaner gas resulting from downdraft operation. Apart from the reactor, the complete system includes a gas cleaner, a cooler and a mixing box; cleaning is achieved by cyclone, scrubbers (for stationary systems), and filters. Cooling is achieved by water (stationary systems) or air (mobile systems) systems. The mixing box is a two-valve system connected to the acceleration pedal and controlling the air and gas flows.

The gas produced from charcoal (and air) has an energy content of 1,300 to 1,700 kcal per cubic meter (150 to 190 Btu per cubic foot) at normal temperature and pressure. Operating a diesel engine on producer gas reuslts in a reduction of diesel fuel usage of 50 to 80 percent of the original (diesel fuel alone) consumption and a loss of power of 5 to 15 percent. Operation of gasoline engines on producer gas resulted in a reduction in power of about 10 percent. Road tests showed that 1 kg of charcoal or 4 kg of wood chips provide the equivalent power and mileage of 1 liter of gasoline.

Estimated capital costs range from about $50 per kW for gasifiers of about 50 kW capacity to about $120 per kW for gasifiers of 10 to 20 kW capacity. Under conditions prevailing in the country, the straight payback period for gasifier units ranges from about 6 months for vehicular applications, to about 1 year for irrigation and power generation, to about 2 years for fishing boats and to 2 to 4 years for various other applications.

2. IMPLEMENTATION FACTORS: Some gasifiers have been in application for over 2 years. The analysis of the experiment conducted in the country suggest that gasifiers are a viable alternative technology to replace or displace liquid fossil fuels. The Farm System Development Corporation hopes to have 1,100 gasifier-fueled irrigation units (about 65 hp each) in operation within 3 years. The Philippine Gasifier Manufacturing Company (GEMCOR) is developing and plans to manufacture units for vehicular application and for fishing boats. The handbook prepared by GEMCOR provides operation and maintenance instructions, a troubleshooting guide and safety recommendations.

3. ENVIRONMENTAL FACTORS:- Not discussed.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: See articles quoted in Entry Statement No. 2.

5. OJBECTIVE OBSERVATIONS: Few data are provided on the design of the system, quality of the gas, environmental aspects, detailed performance, or national policy for resource/fuel utilization. The manufacture and commercial infrastructure appears to be in place for implementation of a large-scale national program.

6. SUBJECTIVE OBSERVATIONS: None.

ENTRY STATEMENT NO. 4

1. VIABILITY FACTORS: A small experimental downdraft gasifier was operated using coconut charcoal as the main feedstock at the Mechanical Engineering Department of the University of the Philippines. The producer gas from this gasifier was used to run a small 3.7 kW (5.0 hp) diesel engine. The only modification necessary to allow the diesel engine to use producer gas was the addition of a gas line connection to the air intake pipe of the engine and appropriate control valves to proportion the air-gas mixture. Diesel or coconut oil was used as startup fuel. After the engine was started, the gas intake valve was opened. As the engine sucked producer gas from the gasifier, the liquid fuel intake steadily decreased until the engine was powered by 90 percent producer gas and 10 percent oil. The gasifier had a 15.2 cm (6 in) diameter throat in the combustion zone giving an area of roughly 181 cm^2 (28 in^2). The height of this gasifier vessel was about 376 cm (148 in). The air inlet holes were spaced 7.68 cm (3 in) apart around the combustion zone. The gas produced ranged in heating value from 4,103 to 4,849 kJ/m^3 (110 to 130 Btu/ft^3). A small cyclone filter was used for gas cleaning. The diesel engine used in the experiment was a single-cylinder engine; it had a bore of 11.4 cm (4.5 in) and a stroke of 10.9 cm (4.25 in). Its compression ratio was approximately 14. The engine ran successfully on a mixture of 90 percent producer gas and 10 percent diesel or coconut oil. The thermal efficiency of the engine in this dual fuel operation was about 18.4 percent which is higher than the thermal efficiency (13 to 15 percent) obtained using straight diesel or coconut oil. The power output of the engine decreased with increasing percentage use of producer gas. This was explained by the fact that the producer gas has lower energy content than the original diesel fuel.

2. IMPLEMENTATION FACTORS: The study shows that coconut shell charcoal is a suitable fuel for a gas producer supplying fuel to a small diesel engine without the use of a complicated gas-cleaning system. However, the use of biomass feedstocks like raw coconut shell, coal dust, and rice hulls has not yet been tried in the gasifier.

3. ENVIRONMENTAL FACTORS: The diesel engine ran on producer gas and emitted a clear smokeless exhaust running at full load. Diesel fuel crude and coconut oil produced a smokey exhaust at even less than full loads.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: Future studies of this type should study the use of agricultural residues like coconut shells, wood wastes, coir dust, and rice hulls in the reactor. A discussion of quantities of feedstock required would have been helpful in this report. A comprehensive and detailed presentation of the experiment results is available as an appendix to this paper.

6. SUBJECTIVE OBSERVATONS: Certain technical descriptions about the system design are lacking in the report.

LARGE-SCALE GASIFICATION

Detailed information and data on different aspects of large-scale biomass gasification systems are presented in the state-of-the-art review references below:

> Gasification: Small and Large Systems and their Use. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

Selected data and information on different aspects of large-scale biomass gasification systems are found in the entry statements presented in this section. The entry statement index, Table C-VII, should be used to narrow the search for the desired data entries. The location of entry statements and the corresponding literature sources are indicated in Table C-VIII.

TABLE C-VII

ENTRY STATEMENT INDEX FOR LARGE-SCALE GASIFICATION

	Entry Number
Source of Data (Countries):	
Brazil	2
U.S.	1,3,4
Data Type:	
Laboratory or bench-scale experiment	
Pilot/demonstration tests	2,3,4
Commercial systems	
- Small	
- Large	1
General	
Biomass Feedstocks:	
Wood and wood waste	1,2,4
Agricultural waste	1,3
Urban solid waste	

TABLE C-VIII

SOURCE AND LOCATION OF ENTRY STATEMENTS

Entry Statement Number and Page		Literature Source
1	C-403	"Charcoal Burner and Waste Heat System," J. Rienks, Forest Products Research Society Proceedings, No. P-75-13, 1973, pp. 89-91.
		"Process Gas from Charcoal Production Supplies 80 Percent of Energy for Process Steam at an Oregon Lumber Mill," in Biomass Energy Success Stories, U.S. Department of Energy, HCP/TO285-01, March 1978.
2	C-404	"Methanol from Wood in Brazil," V. B. Filho and A. J. Zagatto, paper presented at the American Chemical Society National Meeting Houston, Texas, U.S., 1980.
3	C-405	"Food, Forest Wastes: Low-Btu Fuel," J. R. Goss, Agricultural Engineering, January 1978: pp. 30-37.
4	C-406	"Some Practical Aspects Affecting the Operation of a Commercial Gas Producer on Biomass," G. Fimie, Energy from Biomass and Wastes, Institute of Gas Technology, January 1980: pp. 567-576.

ENTRY STATEMENT NO. 1

1. VIABILITY FACTORS: The Olson-Lawyer Lumber Inc. company in Medford, Oregon, U.S., converts about 90 million board feet of lumber annually into a variety of products: lumber, green veneer, wood chips for paper manufacture, and sawdust and shavings for conversion to particle boards. Bark residues are converted to charcoal at a rate of about 7,200 kg/hr (16,000/hr). The charcoal manufacturing unit is a 45-foot high Nichols Herreschoff furnace with a retention time of about 45 minutes. During that time, all the volatile matter is driven off and the remaining charcoal leaves the furnace to be cooled, pulverized, and compressed into briquettes.

The process off-gases leave the furnace through stacks at the top and are pulled through a refractory-lined duct by a stainless steel fan and injected into a steam boiler. In the boiler, the gases are burned with shredded wood residues to raise steam at a rate of about 14,500 kg/hr (32,000/hr). Small natural gas burners are used to ensure the ignition of the process gas. The steam generated in the boiler is used in the lumber steam vats and in the drying kilns.

2. IMPLEMENTATION FACTORS: Fuel handling and furnace control apparently created some startup problems. -These problems have been rectified, and the system is operating satisfactorily. The objective of total log utilization has been achieved.

3. ENVIRONMENTAL FACTORS: No data are provided; the report however does state that good environmental standards have been maintained.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: The system described here results in the complete utilization of the feedstock resource used by the mill. More data concerning the energy balance of the system, gas quality, gas handling, etc., should be obtained.

6. SUBJECTIVE OBSERVATIONS: None.

ENTRY STATEMENT NO. 2

1. VIABILITY FACTORS: The production of methanol by gasification of wood and charcoal and subsequent synthesis has been tested in a pilot plant in Rio Claro, Brazil. The plant currently produces 20 kg/hr (44 lb/hr) of methanol using synthesis gas (or medium-heat-value gas) produced in two charcoal gasifiers. The capacity of this plant will increase to 42 kg/hr (92 lb/hr) of methanol, when the third gasifier, using wood, is added to the present system. These test gasifiers are electrically heated, and the maximum temperature reached in these gasifiers is around 1,250°C (2,282°F). The final gas temperature is 85°C (185°F). It is cooled to 50°C (122°F) by direct contact with a water spray, and then washed. The product gas passes through a dewatering column and is compressed to 5.00 MPa (735 psia) pressure using a three-stage compressor having a rated capacity of 64 m^3/hr (2,300 scf/hr) of synthesis gas. The product gas at this stage has a hydrogen-to-carbon monoxide molar ratio of about 1.30. A part of this gas is sent to a shift converter, where high pressure superheated steam, in the presence of a catalyst, converts carbon monoxide (CO) to hydrogen (H_2) and additional carbon dioxide (CO_2). The gas from the shift converter, when mixed with the rest of the product gas yields a final synthesis gas having a hydrogen-to-carbon monoxide ratio of more than 2.0. The shift reactor (or converter) is made of stainless steel and operates at 500°C (932°F) in presence of an iron oxide catalyst. The methanol converter consists of two stainless steel columns, in series, operating at 300°C (572°F) and 5.00 MPa (735 psia), and uses a copper-based catalyst.

Future Brazilian efforts in wood gasification technology will focus on the design and construction of demonstration-scale plants, producing about 100 tonne (110 tons) of methanol per day using about 300 tonne (330 tons) of wood per day.

2. IMPLEMENTATION FACTORS: Large-scale wood gasifiers suitable for methanol synthesis are not commercially available today. The main objectives of the pilot wood gasification project are:

- o to obtain technical and operational data for future scaleup of wood gasification plants
- o to evaluate Brazilian capability in equipment manufacture, design, engineering, and erection of gasification systems, high pressure plants, methanol synthesis, etc.
- o to promote training of operators

3. ENVIRONMENTAL FACTORS: Not discussed.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: Data reported here are obtained from pilot wood gasification and methanol synthesis tests. Data on certain important operating parameters, such as gasifier wood feed rate, quality of wood feed (size, moisture content), and steam and oxygen usage, are not reported. Also, the type of gasifiers used and their diameters are not mentioned.

6. SUBJECTIVE OBSERVATIONS: The authors attempted to present the need for an alcohol fuel, particularly methanol, industry in Brazil. Technical and economic data are sketchy.

ENTRY STATEMENT NO. 3

1. VIABILITY FACTORS: A pilot downdraft gasifier operated successfully by the University of California, Davis, California, U.S., on a mixture of mulled and raw walnut shells producing a combustible gas composed of 19 percent carbon monoxide, 17 percent hydrogen, and 6 percent hydrocarbons (mostly methane). The rest was carbon dioxide, water vapor and nitrogen. The design fuel (walnut shells) rate of the gasifier is about 636 kg/hr (1,400 lb/hr) which can produce about 8.4 GJ/hr ($8x10^6$ Btu/hr) of product low-heat-value gas. Excluding the fuel feed and the ash removal systems, the unit (gasifier) weighs 3.5 tonne (3.9 tons) and is 5.2 m (17.25 ft) high, and the grate diameter is 1.9 m (6.3 ft). The fuel feed system includes a storage tank (6.2 m^3 or 217 ft^3 capacity), feed auger, continuous flow metering device, and an airlock feed valve that has a capacity of 2.2 m^3/hr (80 ft^3/hr). The solid refuse airlock valve has a capacity of 3.4 m^3/hr (120 ft^3/hr). The capital cost of the gasifier and other related equipment is about $125,000 (1977 U.S. dollars).

The gasifier will be used to run internal combustion engines and oil- and gas-fired boilers at several food processing plants in California, U.S. Preliminary tests have successfully demonstrated the use of product low-heat-value gas in a natural gas-fired boiler producing about 3,860 kg/hr (8,500 lb/hr) of low-pressure steam.

2. IMPLEMENTATION FACTORS: The pilot gasification project is a result of a cooperative effort between the California Energy Resources Conservation and Development Commission and local food and forest industries producing biomass feedstock as their process waste.

3. ENVIRONMENTAL FACTORS: Not discussed.

4. RELATED PAPERS SUGGESTED FOR FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: Results reported in this paper are obtained from a pilot gasifier operating at a walnut-processing plant in Stockton, California, U.S. It is mentioned that the product low- heat-value gas fuels a natural-gas-fired steam boiler. However, the modifications necessary to burn the low heat value gas in a natural-gas-fired boiler are not reported.

6. SUBJECTIVE OBSERVATIONS: Useful operating data on a pilot-scale biomass gasifier are given in this paper.

ENTRY STATEMENT NO. 4

1. VIABILITY FACTORS: The results of operating a pilot biomass gasifier and burning the gas in a boiler are reported here. Various dry maple (wood), hog fuel (chipped wood waste and bark) mixture, and green sawdust samples were gasified. The moisture content of the feedstock ranged between 10 to 60 percent wet basis. Different sized feedstocks ranging from coarse to fine, were used in the gasification experiments. The particle sizes ranged from 0.5 to 2.8 cm (0.18 to 1.12 in). The higher heating value of the gas ranges from 3,500 to 7,460 kJ/m^3 (94 to 200 Btu/ft^3). Combustion of raw hot gas in an existing boiler has proved to be difficult because of the presence of large quantities of water vapor in the hot product low-heat-value gas. The water and other organic vapors should be removed from the gas before it can be ignited rapidly and burned smoothly without any difficulty. It has been found that scrubbing does not reduce the heating value of the product gas significantly. On the contrary, the water vapor in unscrubbed gas reduced the heating value and flame temperature substantially. For example, a maximum flame temperature of 1,204°C (2,200°F) is obtained by burning the unscrubbed gas. To avoid problems with tar condensation, the gas should be cooled to 27°C to 38°C (80°F to 100°F) and then scrubbed. This scrubber separator system removes all particles above 5 microns size. If the gas is to be burned in a burner, no further cleaning is required. However, for gas turbines it has to be cleaned further to remove all particulates over 0.5 microns. Burners capable of burning low-heat-value gas are available in the size ranging from 211,000 to 105x10^6 kJ/hr (200,000 to 100x10^6 Btu/hr). These burners require 2 to 5 cm (1 to 2 in.) water-column pressure and have a turn-down ratio of 10 to 1.

2. IMPLEMENTATION FACTORS: Not discussed.

3. ENVIRONMENTAL FACTORS: The low-heat-value gas product gas when burned in an existing boiler did not produce any air pollution due to particulate emissions.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: The biomass feed rate of the gasifier is not mentioned. Also, the dimensions, particularly the internal diameter of the gasifier, are not given. The operating difficulties of fixed-bed updraft gasifiers are caused by the presence of large quantities of condensable tars in the product gas. However, if the temperature of the raw hot gas is kept above the condensation temperature of the tar, its combustion should not cause any difficulty. It is not clear whether the raw hot product gas is burned in a close-coupled boiler or whether it is piped over a reasonable distance, which may have promoted tar condensation in the boiler.

6. SUBJECTIVE OBSERVATIONS: This paper describes the common operating problem of a fixed-bed updraft gasifier. The author's strong conclusion regarding the inability of a raw hot gas to burn should be taken as a case-specific operating difficulty rather than a general technical problem.

PYROLYSIS

Detailed data on pyrolysis technology are presented in:

Pyrolysis: Charcoal, Pyrolytic Oils, Fuel Gas and their Use. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

Selected data on pyrolysis technology are presented in the entry statements in this section. The entry statement index, Table C-IX, is designed to aid readers in their search for specific data entries. The location of entry statements and the corresponding literature sources are indicated in Table C-X.

TABLE C-IX

ENTRY STATEMENT INDEX FOR PYROLYSIS

Source of Data (Countries):	
Indonesia	1
United States	2,3,4
Data Type:	
Laboratory or bench-scale experiment	3
Pilot/demonstration tests	1,2
Commercial systems	
- Small	
- Large	4
General	
Biomass Feedstocks:	
Wood and wood waste	2,3,4
Animal waste	
Crop residue	1,2,3,
Municipal solid waste	2,3,

TABLE C-X

SOURCE AND LOCATION OF ENTRY STATEMENTS

Entry Statement Number and Page		Literature Source
1	C-503	"Third World Applications of Pyrolysis of Agricultural and Forestry Wastes," J. W. Tatom et al., presented at the National ACS Symposium, September 10-14, 1979, Washington, D.C., U.S.
2	C-505	"Pyrolysis—A Method of Conversion of Forestry Wastes to Useful Fuels," J. A. Knight et al., presented at the Conference on Energy and Wood Products Industry, Forest Products Resarch Society, November 15-17, 1976, Atlanta, Georgia, U.S.
3	C-506	"Fuels from Biomass by 'Flash Pyrolysis'$^{\mathrm{TM}}$," G. T. Preston, Occidental Research Corporation, presented at Texas Tech/DOE Symposium Thermochemical Conversion of Biomass Residues, November 30, 1977, Golden, Colorado, U.S.
4	C-507	"On Site Burning of Industrial Residues Provides Energy to Heat an Entire Manufacturing and Warehousing Facility," in Biomass Energy Success Stories, U.S. Department of Energy, HCP/TO285-01, Washington, D.C., March 1978.

ENTRY STATEMENT NO. 1

1. VIABILITY FACTORS: A simple rice husks pyrolysis unit has been operating in Bandung, Indonesia. Similar units were tested in Ghana and Philippines. The system being tested in Indonesia uses an improved design configuration to eliminate some of the obstacles to the material (and fluid) flow experienced in earlier designs tested in Ghana and Philippines. The pyrolysis converter uses a partial oxidation pyrolysis process to convert rice husks into pyrolytic oil, char and low-heat-value gas. The converter stands 2.35 m (7.7 ft) tall, has a base diameter of 0.84 m (2.75 ft) and a top diameter of 0.7 m (2.3 ft). It is built of mild steel, typically 2-to-3 millimeters (0.078 to 0.110 in.) thick. Instrumentation includes a process air flow orifice and dial thermometers for measuring bed, converter off-gas, and condenser off-gas temperature. The converter can process about 100 kg/hr (220 lb/hr) of rice husks, which are added at the top of the converter through a quick disconnect inlet feed port and the charcoal removed at the bottom through a single sliding grate. Process air is introduced near the bottom of the system and passes upward to exit through the off-gas system and then enters the condenser/demister which recovers the product oil. For proper operation of the pyrolysis system, the converter and the condenser off-gas temperatures should be controlled. Each feedstock has a different optimum temperature range. For rice husks with a moisture content of about 11 percent and ash content of 20 percent and at a bed depth of 0.3 m (0.98 ft), the desired convertor off-gas temperature lies between 120°C to 140°C (248°F to 284°F) and the condenser off-gas temperature is around 85°C (185°F). The results so far have indicated very low oil yields and higher char yields compared with the original expectations. For example, at an air- to-feed ratio of 0.633 kg/kg dry ash free, the recovered oil yield is about 0.033 kg/kg of dry ash free feed, while the char yield is about 0.25 kg/kg of dry ash free feed. The lower oil yields are attributed to the poor performance of the oil separator (i.e. condenser/demister). The char is of good quality, and it has been successfully briquetted to form "fire balls" by means of a simple agglomeration technique in which waste cassava pulp from a local starch mill is used as a binder. The oil is very thick, and after proper treatment can be burned in conventional fuel combustion systems. The product gas burned clearly, completely, and without odor in both diffusion burners and a forced air combustor designed for crop-drying applications.

The total pyrolysis system cost including convertor, air supply, char briquetting equipment, small engine-generator, operating platform, and feed storage is $2,500 (1980 U.S. dollars).

2. IMPLEMENTATION FACTORS: Many countries face extraordinary problems in meeting the energy demands required for development, especially because of a general lack of foreign exchange. They are also confronted with high levels of unemployment, and have the mixed blessing of low wages. Therefore, a simple pyrolysis system that could engage many people in its operation would be easy to implement. However, the existing heavy fossil fuel subsidies may affect the economic competitiveness of this technology.

3. ENVIRONMENTAL FACTORS: Particulates, SO_x and NO_x emissions are negligible.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: "Pyrolytic Conversion of Agricultural and Forestry Wastes in Ghana—A Feasibility Study," T. I. Chiang et al. Report under AID contract AID/TA-C-1290, EES, Georgia Tech, Atlanta, Georgia, February 1977.

5. OBJECTIVE OBSERVATIONS: Successful implementation of any pyrolysis project depends on the availability of markets for pyrolytic char, oil, and

gas. It should be noted that direct interchangeability of pyrolytic fuels, derived from rice husks, with conventional pretroleum-derived fuels in a combustor will be difficult. More product characterization data are required to assess the end-use markets.

6. SUBJECTIVE OBSERVATIONS: The authors of this report have favored the implementation of very simple and small-scale pyrolysis systems in the rural areas of developing countries. However, the availability of biomass feedstock and of a market for the pyrolysis products (char, fuel gas and pyrolytic oil) should be confirmed before such a venture is undertaken.

ENTRY STATEMENT NO. 2

1. VIABILITY FACTORS: A pyrolysis process developed and field tested at Georgia Institute of Technology has been licensed to the Tech-Air Corporation in Atlanta, Georgia. The Tech-Air Corporation has built and successfully operated a 45-tonne per day (50 ton per day) pyrolysis demonstration plant. It operates under steady flow and low temperature and uses a porous vertical bed updraft design reactor. The system includes a waste-receiving bin, a belt conveyor to the converter, a converter and char-handling system, off-gas cyclone, condenser by-pass, demister, draft fan and vortex after burner. The system produces char and pyrolytic oil that are sold as a fuel and off-gases used to dry the feedstock; extra gas is flared. A dryer which utilizes hot combustion gases from the off-gas burner reduces the water content of the feedstock to 4 percent.

Input feedstock varies in moisture content from 20 percent to 55 percent. Types of feedstock used include peanut hulls, wood chips, pine bark, sawdust, used tires, municipal wastes, macademia nut hulls, and cotton gin wastes. Pyrolytic yields from feedstocks that can be used as fuels are: char, 23 percent; pyrolytic oil, 25 percent; noncondensable gases, 68 percent; and water vapor, 33 percent. The yield is greater than 100 percent since the noncondensed--gases contain nitrogen from the process air. The energy balance indicates that char and pyrolytic oil each account for 35 percent of the derived energy; noncondensed gases, 21.7 percent, and heat losses, the remainder. Heating values for char vary from 25,520 kJ/kg to 30,160 kJ/kg (11,000 Btu/lb to 13,000 Btu/lb); for pyrolytic oil, from 23,200 to 30,160 kJ/kg (10,000 Btu/lb to 13,000 Btu/lb); and for the noncondensed gas, a low-Btu gas, in the range of 7,460 kJ/m^3 (200 Btu/ft^3). This gas must be burned on-site and is sufficient for drying feedstock down to 4 percent moisture content.

2. IMPLEMENTATION FACTORS: Experimental and demonstration plants have shown this process to have favorable economics but the factors for each case must be assessed to develop accurate cost figures. Some economic factors that should be considered include:

1) site location and preparation

2) availability of feedstock (45 tonnes or 50 dry tons of waste per 24-hour period)

3) marketing of end products

3. ENVIRONMENTAL FACTORS: Waste materials are converted to useful fuels in a nonpolluting manner, thereby eliminating disposal problems. The system easily meets all U.S. federal environmental standards. In-plant use of the off-gases from the pyrolytic process limits the heat and air pollution problems from gas flares.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: Organizations interested in this process should contact the licenser, and Tech-Air Corporation, 2231 Perimeter Park, Suite 16, Atlanta, Georgia 30341, U.S. Reference papers are cited in reference 2 (Table C-X).

5. OBJECTIVE OBSERVATIONS: The water pollution hazards of soluble organic chemicals in the plant effluent stream are not mentioned. Markets for char and pyrolytic oils are not discussed.

6. SUBJECTIVE OBSERVATIONS: This paper presents a concise and informative briefing of the pyrolysis process. A more in-depth discussion of economic factors including system procurement, construction operation, and maintenance costs is recommended. More data on feedstock mixes and quantities and environmental issues are needed.

ENTRY STATEMENT NO. 3

1. VIABILITY FACTORS: Municipal solid wastes, forest wastes, rice hulls, and other organic wastes have been converted to clean-burning liquid and gaseous fuels by flash pyrolysis. In this process, the biomass feedstock is pyrolyzed at moderate temperature, under low pressure using short residence time. When municipal solid waste is the feedstock, extensive front-end pretreatment is required to separate the inorganic fraction from the organic fraction. Other biomass feedstocks, except for drying and size reduction, do not require extensive preprocessing.

The finely shredded biomass feed material is carried into the reactor by recycled product gas. The pyrolysis takes place at about 507°C (950°F) at a pressure of about 200 kPa (1 atmosphere gauge). No air, oxygen, hydrogen, or catalyst is used in the pyrolysis process. Upon leaving the reactor, the solid residue (char) is separated from product vapors in cyclone separators. The char is combusted to supply the pyrolysis heat to the reactor. Following a separation of the solids, the pyrolytic product vapors are quenched rapidly to prevent the large-molecule oil components from cracking further to less desirable products. The useful end products are separated into pyrolytic oil, gas, and water.

This process has been tested by Occidental Research Corporation in California, U.S. Data for a bench-scale system is presented below.

Bench-scale Tests. These tests were conducted during the early seventies. The bench-scale reactor was a 2.54-cm (1 in) diameter stainless steel pipe equipped with external electrical resistance heating. This unit was capable of processing 4 kg/hr (8.8 lb/hr) of biomass feedstock. Nitrogen was used as a carrier gas. This unit was not capable of using recirculating solids to provide pyrolysis heat. Because of the heat transfer limitation, the particle size of the feedstock had to be kept under 74 microns (200 mesh). This system is used to provide extensive product yield and composition data on a variety of biomass feedstocks. It has operated for a total of 1000 hours. The cost of this system in 1970 was about $150,000 (U.S. dollars).

2. IMPLEMENTATION FACTORS: In November 1977, when this article was published, successful demonstration of this technology had not been completed. The technology and equipment design are complex and geared towards the processing of municipal solid waste. Also, the economics of providing an acceptable quality liquid fuel has yet to be shown. Systematic approach of Occidental Research Corporation's going from bench-scale to pilot-scale testing and then to a demonstration project will help in the actual implementation of the project.

3. ENVIRONMENTAL FACTORS: Not discussed.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: Reference papers are cited in reference 3 (Table C-X).

5. OBJECTIVE OBSERVATIONS: The residence time of feed material in the pyrolysis reactor is omitted. Extensive characterization of product oil should be conducted before its utility can be confirmed.

6. SUBJECTIVE OBSERVATIONS: The author has presented a very convincing argument for the viability of flash pyrolysis. In the absence of any large-scale-plant operating data, optimism should be cautious.

ENTRY STATEMENT NO. 4

1. VIABILITY FACTORS: The K. W. Muth Co. in Sheboygan, Wisconsin, uses a pyrolytic converter to dispose of its scrap wood. The combustible gases generated by the pyrolytic incinerator are used to heat 8,500 square meters (91,000 square feet) of manufacturing space and warehouse area. The residues used are particle board and hardwood scraps.

The residues are fed into a pyrolytic chamber where thermal dissociation and gasification take place in an oxygen-lean atmosphere. The combustible gases driven off are ignited and completely burned in a thermal reactor in the presence of an excess of air. The hot flue gases are then passed through a boiler where heat is exchanged to produce steam for the plant heating system. The cost of the system was $100,000 in 1976. Indications are that the heat recovery and pyrolytic disposal system will pay for itself in 2 years or less.

2. IMPLEMENTATION FACTORS: Since operation of the system began in 1976, basic startup problems have been solved and residues are consumed at a rate of 70 to 100 tons per week. At this rate, only half of the heat generated is used to fire the boiler, and plans are underway for using some of the additional heat for paint drying operations, thereby increasing the fuel savings.

3. ENVIRONMENAL FACTORS: Pollution problems associated with this method of combustion are negligible because very little particulate matter is entrained in the flue gases.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: Further data concerning the operation and maintenance requirements and costs should be obtained and evaluated.

6. SUBJECTIVE OBSERVATIONS: None.

BIOMASS CHAR-OIL SLURRY COMBUSTION

Detailed data on biomass-derived char-oil mixture (BCOM) combustion technology are presented in:

Combustion: Stoves and Boilers. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

Selected data on BCOM combustion technology are presented in the entry statements in this section. The entry statement index, Table C-XI, is designed to aid readers in their search for specific data entries. The location of entry statements and the corresponding literature sources are indicated in Table C-XII.

TABLE C-XI

ENTRY INDEX FOR CHAR-OIL SLURRY COMBUSTION

	Entry Number:
Source of Data (Countries):	
U.S.	1,2,3
Data Type:	
Laboratory or bench-scale experiment	
Pilot/demonstration tests	1,2,3
Commercial systems	
- Small	
- Large	
General	
Biomass Feedstocks:	
Wood and wood waste	1
Agricultural waste	
Urban solid waste	

TABLE C-XII

SOURCE AND LOCATION OF ENTRY STATEMENTS

Entry Statement Number and Page		Literature Source
1	C-603	"Combustion of Low-Sulfur-Low-Nitrogen Char Produced by Pyrolysis of Wood Wastes," J. J. Demeter, et al., *Energy from Biomass and Wastes*. Institute of Gas Technology, September 1978: pp. 275-293.
2	C-604	"Recent Coal-Oil Combustion Tests at PECT," Y. S. Pan et al., presented at the 1980 spring meeting, Combustion and Utilization of Alternative Fuels, Central States Section The Combustion Institute, Louisiana State University, Baton Rouge, Louisiana, March 24-25, 1980, paper No. CCS/CI-80-17.
3	C-605	"A Demonstration of Coal-Oil Mixture Combustion in an Industrial-Scale Boiler," A. Shimizu and T. Derbidge, in-house paper of Acurex Corporation, Mountain View, California; work performed under contract number EF-77-C-01-2563, undated.

ENTRY STATEMENT NO. 1

1. VIABILITY FACTORS: The combustion characteristics of a biomass-derived char-oil mixture (BCOM) are determined in a residual oil-fired boiler at the Pittsburgh Energy Research Center in the U.S. Department of Energy. The boiler is a fire tube design, with a rated capacity of 4 GJ/hr (100 hp). The BCOM is prepared by using the char and pyrolytic oil from the wood pyrolysis tests, conducted at the Georgia Tech Experiment Station, Atlanta, Georgia, U.S. (see Pyrolysis). A 60-40 blend of low volatile char and pyrolytic oil is combined with residual oil to produce a slurry. The slurry was kept well mixed using a mechanical stirrer. The BCOM fuel has about 90 percent of the heating value (higher heating value) of the residual fuel oil, and it contains slightly lower amounts of hydrogen and carbon. Its oxygen and ash content are higher than residual fuel oil. The viscosity of BCOM fuel is about 225 cp at 60°C (140°F) compared to 82 cp for the residual fuel oil. During the combustion test period excellent flame stability was observed. Loss of carbon in the stack experienced with BCOM is about the same as that with residual fuel oil (about 0.3 percent), and this is substantially lower than the loss of carbon observed with coal-oil mixture (COM) combustion (about 1.3 percent). Some fouling of the small parts in the burner nozzle was observed due to the accumulation of small fibers that passed through the filter screen. This problem is alleviated by a slight modification of the nozzle.

2. IMPLEMENTATION FACTORS: Not discussed.

3. ENVIRONMENTAL FACTORS: The combustion of BCOM in a residual-oil-fired boiler resulted in lower oxides of nitrogen and sulfur emissions than that obtained from COM combustion. Higher particulate loading is obtained for BCOM combustion when compared with residual-fuel oil firing.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: Demeter, J. J., et al., "Combustion of Coal-Oil Slurry in a 100 hp Fire-tube Boiler," PERC/RI-77/8, May 1977.

5. OBJECTIVE OBSERVATIONS: BCOM used in the combustion tests contained pyrolytic oil. The corrosion and other handling problems of this oil are not mentioned.

6. SUBJECTIVE OBSERVATIONS: Some useful data on BCOM combustion are presented. However, long-duration combustion tests are required before the use of BCOM as a substitute for residual oil in industrial and utility combustion equipment is seriously considered.

ENTRY STATEMENT NO. 2

1. VIABILITY FACTORS: Coal-oil mixture (COM) combustion tests with coal concentration up to 50 percent by weight have been successfully conducted at the Pittsburgh Energy Research Center of the U.S. Department of Energy. A water-tube boiler, capable of producing 10,896 kg/hr (24,000 lb/hr) of saturated steam at 1,308 kPa (175 psig), originally designed for oil firing is used in these tests. The fuel storage consists of an insulated 227,400 L (60,000 gal) capacity residual-fuel-oil storage tank and a 24-tonne (26-ton) coal storage bin. Coal is ground, dried, and classified by a pulverizer so that 90 percent pass through a 200 mesh. The dry pulverized coal is stored in a 14.5-tonne (16-ton) capacity coal supply hopper. Coal-oil mixtures are prepared in a 6,822 L (1,800 gal) capacity, steam-jacketed mix tank which incorporates an agitator comprised of two sets of turbine blades. A predetermined amount of No. 6 fuel oil is charged into the mix tank. Pulverized coal is then added to the tank from the coal supply hopper through a vertical gravimetric coal feeder at the rate of 2,000 pounds per hour. The coal-oil mixture is then transferred to a 2,800-gallon steam- jacketed holding tank incorporating an agitator with one set of turbine blades. The coal-oil mixture is continually recirculated from the bottom of the tank to the top by a Viking rotary pump. The COM feed pump is a progressing-cavity pump driven by an adjustable speed drive DC motor. The feed rate of COM through the burner is regulated by this variable-speed feed pump. A steam-atomized residual oil burner is modified to fire COM. The modifications mainly include changing of the materials of construction to withstand the abrasive properties of the COM. A 500-hour duration combustion test with 40 percent coal-oil mixture has been successfully completed. Analysis of test results shows that there is no derating of the oil-fired boiler using COM. Carbon conversion efficiencies have been generally above 98 percent, and boiler efficiencies are about the same as those when firing residual fuel oil. These long-duration test data also showed that continuing furnace ash accumulation could interrupt the boiler operation. In addition, wear at the burner nozzles has been significant. However, furnace ash deposition can be handled with soot blowers, and the problem of nozzle wear can be remedied by selecting abrasion- resistant burner nozzle tips.

2. IMPLEMENTATION FACTORS: Not discussed.

3. ENVIRONMENTAL FACTORS: The emission of oxides of nitrogen (NO_x) increased with the increase of nitrogen content due to the coal content in the fuel and operating excess air level. The emission of SO_x is dependent on the sulfur content in the fuel. The fly ash emission and furnace ash accumulation are dependent on the ash content in the fuel.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: See cited references papers in report.

5. OBJECTIVE OBSERVATIONS: Actual operating data of a small residual-oil-fired boiler burning COM are presented in this paper. In spite of the apparent similarity between coal-oil mixture (COM) and biomass-derived char-oil mixture (BCOM) fuels, the combustion data and operating difficulties mentioned in this paper may not all directly apply to BCOM combustion.

6. SUBJECTIVE OBSERVATIONS: Useful COM combustion and environmental data are presented in this paper. The authors convincingly illustrate the technical feasibility of COM combustion in existing residual-oil-fired boilers. However, long-term effects of corrosion, erosion, and fouling of boiler and other equipment still need to be determined.

ENTRY STATEMENT NO. 3

1. VIABILITY FACTORS: A description of a planned commercial coal-oil mixture (COM) preparation and combustion demonstration program is given in this paper. The COM preparation plant has been designed to simulate a large central preparation and distribution facility.

Major elements of the COM preparation plant are coal handling and preparation equipment, including a wet-grinding ball mill that simultaneously grinds and blends coal with residual fuel oil. The technical feasibility of wet grinding, which produces a more homogeneous blend than dry grinding, has been proven in several experiments. The ball mill used for wet grinding is about 1.5 m (5 ft) in diameter by 3.9 m (13 ft) long. A ball charge of 11,350 kg (25,000 lb) was used initially. To reduce heat loss through the steel mill shell, a 3.8 cm (1.5 in) layer of insulation will be applied directly to the shell. During operation, the mill turns approximately 35 revolutions per minute. It is an open-circuit arrangement designed to grind coal so that 80 percent of the particles pass through a 200 mesh screen. The coal-oil slurry from the mill is passed through a trommel to remove oversize material and it is stored in a COM storage tank. The equipment that comes in direct contact with COM is made of or coated with erosion-resistant material. It has been observed that the viscosity of COM increases by 10 times as the coal fraction is increased from 40 to 50 percent by weight. However, since reduction in coal fraction adversely affects the economics of COM, the problems of high viscosity are addressed by designing equipment that can handle slurry viscosities as high as 10,000 centipoise (cp). To enhance the stability of COM, chemicals are added which constitute approximately 4 percent of COM weight. The COM storage tank has a capacity of 11,370 L (30,000 gal), and it is equipped with a mechanical stirrer. The fuel storage temperature is expected to be about 60°C (140°F). A modified fuel pump is used to move the COM in the preparation plant and boiler plant. The fuel pump is rated at a maximum discharge pressure of 2,169 kPa (315 psig) at 57 L (15 gal) of COM per minute. A new steam-atomized burner is used to burn COM. It is made of erosion-resistant material and has a flame-shaping capability to avoid any flame impingement on furnace walls, which can lead to slagging. The existing industrial boiler is a Keeler D-type boiler originally designed to burn oil or natural gas. The boiler is rated to produce 36,320 kg/hr (80,000 lb/hr) of saturated steam at 2,171 kPa (300 psig) pressure.

2. IMPLEMENTATION FACTORS: The key to successful commercialization of COM in the industrial boiler sector is a central preparation plant that can serve a large number of users. On-site COM preparation plants to supply fuel to industrial boilers are marginally competitive with delivered prices of residual fuel oil. Larger COM fuel preparation plants take advantage of the available economies of scale and are able to produce COM at lower cost.

3. ENVIRONMENTAL FACTORS: Low-sulfur fuels are used to keep sulfur emissions below the acceptable value. Particulate matter will be removed using a conventional design baghouse.

4. RELATED PAPERS AND SUGGESTED FURTHER READING See cited reference papers in the report.

5. OBJECTIVE OBSERVATIONS: Data presented are the design data for a planned COM industrial combustion demonstration project. The applicability of these data to BCOM combustion should be carefully evaluated.

6. SUBJECTIVE OBSERVATIONS: Some of the conclusions presented need to be supported by the actual operating data from the demonstration project, especially, the technical feasibility of wet grinding.

HYDROLYSIS

Detailed data on hydrolysis technology are presented in:

Alcohol Fuels: Ethanol, Methanol and their Use. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

Selected data on hydrolysis technology are presented in the entry statements in this section. The entry statement index, Table C-XIII, is designed to aid readers in their search for specific data entries. The location of entry statements and the corresponding literature sources are indicated in Table C-XIV.

TABLE C-XIII

ENTRY STATEMENT INDEX FOR HYDROLYSIS

Sources of Data (Countries):	
U.S.	1,2,3
Data Type:	
Laboratory or bench-scale experiment	
Pilot/demonstration tests	
Commercial systems	
- Small	
- Large	1,2,3
General	
Biomass Feedstocks:	
Wood and wood waste	1,2,3
Crop residue	
Municipal solid waste	1

TABLE C-XIV

SOURCE AND LOCATION OF ENTRY STATEMENTS

Entry Statement Number and Page		Literature Source
1	C-703	"Economic Update of the Gulf Cellulose Alcohol Process," G. H. Emert, R. Katzen, R. E. Fredrickson, and K. F. Kaupisch, Katzen Associates, Cincinnati, Ohio, Chemical Engineering Process, September 1976.
2	C-704	"Chemicals from Wood Waste," R. Katzen and Associates, prepared for Forest Products Laboratory, Madison, Wisconsin, December 24, 1975.
3	C-705	"Application of GEMS to Preliminary Process Design and Economic Analysis for an Integrated Wood Hydrolysis Plant," X. N. Nguyen, V. Venkatesch, D. B. Marsland, and I. S. Goldstein, presented at the 89th National American Institute of Chemical Engineers Meeting, August 17-20, 1980, Portland, Oregon.

ENTRY STATEMENT NO. 1

1. VIABILITY FACTORS: The Gulf ethanol production process described is based on 1,814 dry tonnes (2,000 dry tons) per day of raw material, a production of 568,500 L (150,000 gal) per day of 199 proof ethanol, and 484 dry tonnes (534 tons) per day of a by product animal feed. The raw material is two-thirds municipal solid waste and one-third pulpmill waste. Retention time in the simultaneous saccharification and fermentation section is 24 hours. Approximately 15 percent of the raw material is required to produce the enzyme. The carbon dioxide production of 423 tonne (466 tons) per day is not recovered. Total investment for the plant is estimated for 1981 to be $112 million. The economic analysis shows an ethanol production cost of 27 cents per litre ($1.02 per gallon) and a selling price of 38 cents per litre ($1.44 per gallon) (200 proof). This is a more favorable price than from grain fermentation (47 cents per litre or $1.80 per 200-proof gallon, 1981).

2. IMPLEMENTATION FACTORS: The process is based on a new and sophisticated technology, and plant operation requires a high degree of technical supervision. Thus, construction and operation of such a plant would require personnel with training in biochemical process operations. The use of municipal solid waste is suitable only if appreciable amounts of cellulosic materials are present. These cellulosics must be in the form of chemical wood pulps or other materials of low lignin content. Otherwise, they will not be hydrolyzed by the enzymes. The paper content of municipal solid waste of many countries is probably low compared to that in the United States.

3. ENVIRONMENTAL FACTORS: Effluent treatment facilities are included in plant design and operation costs. Since process raw material is solid waste, operation of such a plant would have a positive environmental impact.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: None.

5. OBJECTIVE OBSERVATIONS: The pretreatment necessary to utilize lignocellulosics (in contrast to cellulosics) is not mentioned. The process as described is not capable of utilizing wood, bark, or any agricultural lignocellulosic such as bagasse, rice hulls, or straw.

6. SUBJECTIVE OBSERVATIONS: The plant as described would have to be located so that the solid waste from nearly 1 million people and almost 13,600 tonnes (15,000 tons) daily of pulp capacity would be available. It is doubtful that this much pulpmill residue could be obtained within economic hauling distance of a site that also is near a large population. Even if papermill waste were included along with the pulpmill waste, it would be difficult to locate in any country.

The material balance is based on optimistic values of chemical composition of raw materials and products and yields of products. For example, it shows that only 109 tonne (120 tons) of ash results from the 1,814 tonne (2,000 tons) of raw material. It is likely that more than this amount will result from only the 599 tonne (660 tons) of pulpmill waste used per day.

The report appears to contain contradictory statements about the status of the process. For example, under the heading "Economics," it states: "Clearly, if all technical and economic assumptions can be proved valid, the cellulose alcohol process will be competitive in the alcohol market." In the "Conclusion", it states: "The technical feasibility has been demonstrated by the research work carried out at Gulf Oil Chemicals Co." These statements indicate that there is doubt about the process and that perhaps the ethanol costs from the difficult-to-obtain raw materials may be higher than estimated.

ENTRY STATEMENT NO. 2

1. VIABILITY FACTORS: This report describes the economics of a wood hydrolysis plant based on a 1,342-tonne (1,480-tons) dry basis, per day of Douglas fir wood producing 95 million litres (25 million gallons) per year of 190 proof ethanol. The raw material is wood waste containing 25 percent bark. The yield of ethanol is estimated to be 272 litres of ethanol per tonne of wood (65 gallons per ton) or 205 litres per tonne of wood containing 25 percent bark (49 gallons per ton).

On an hourly basis, the material balance of a plant is 55,933 kilograms (123,000 pounds) of wood waste; 9,171 kilograms or 4,949 litres (20,200 pounds or 3,074 gallons) of ethanol; 545 kilograms (1,200 pounds) of furfural; 454 kilograms (1,000 pounds) of methanol; and 1,861 kilograms (4,100 pounds) of pentoses. Reaction conditions are 0.53 percent sulfuric acid in a percolation digester at a maximum temperature of 198°C (385°F). Total percolation time is 3.9 hours and total cycle time is 4.7 hours.

Total investment is estimated to be $70 million (1975). Economic analysis with a wood cost of $37 per dry tonne ($34 per dry ton) results in an estimated selling price (1975) of $0.50 per litre ($1.90 per gallon) of 190-proof ethanol. The estimated investment of a plant six times larger is $185 million (1975) and an estimated ethanol selling price is $0.37 per litre ($1.42 per gallon).

A credit of $0.44 per kilogram ($0.20 per pound) is assumed for the crude furfural and $0.22 per kilogram ($0.10 per pound) of pentose in a pentose sugar concentrate.

2. IMPLEMENTATION FACTORS: Sale of ethanol would present no problem, but markets for crude furfural and concentrated pentose would have to be developed. The crude furfural could be refined to commercial-grade furfural. The pentose concentrate could be utilized for additional furfural, used as an animal feed molasses, or used as a growth substrate for yeast (protein) growth. Each of these three possibilities is presently in commercial use.

3. ENVIRONMENTAL FACTORS: Environmental effects resulting from the use of the percolation process could be adequately controlled with current technology.

4. RELATED PAPERS AND SUGGESTED FURTHER READING:

U.S. Forest Products Laboratory
1946. "Madison Wood Sugar process." USDA/FS
Forest Products Laboratory
Report No. R1617

Gilbert Nathan, I. A. Hobbs, and J. D. Levine
1952. "Hydrolysis of Wood."
Industrial and Engineering
Chemistry 44(7):1712-1720.

5. OBJECTIVE OBSERVATIONS: This report adequately assesses the feasibility of the dilute sulfuric acid percolation hydrolysis process.

6. SUBJECTIVE OBSERVATIONS: The Madison percolation process is described and assessed economically for the production of ethanol from a softwood species. Even though the process has been used in the United States and is currently in use in a modified form in the USSR, this process is probably not the process of choice for use currently. It should not be used for hardwood species or raw material containing appreciable amounts of hemicellulose because processing conditions result in low recovery of pentose sugars and furfural.

ENTRY STATEMENT NO. 3

1. **VIABILITY FACTORS:** The paper evaluates the process operating variables and presents an economic sensitivity analysis of the concentrated hydrochloric acid process to hydrolyze the wood of a hardwood species. The process consists of: (1) a prehydrolysis reactor where the hemicelluloses are hydrolyzed principally to xylose; (2) a main hydrolysis reactor where cellulose is hydrolyzed to glucose and glucose oligomers leaving a lignin residue; (3) a posthydrolysis reactor for conversion of xylose and other pentose sugars for furfural; (4) a furfural and acetic acid recovery section; (5) fermenters for conversion of glucose to ethanol; (6) an ethanol recovery section; and (7) a hydrochloric acid recovery section.

The wood considered in this evaluation is sweetgum, Liquidambar styraciflua and is comprised of 20.5 percent furfural precursors (xylose and arabinose), 43 percent alpha-cellulose (glucose and mannose), 22 percent Klason lignin, and 3.5 percent acetyl. The wood components are converted in an integrated manner into ethanol, furfural, acetic acid, and lignin.

Operating conditions for the prehydrolysis are liquor-to-wood ratio of 4 with 30 percent hydrochloric acid at 40°C (104°F) for 180 minutes. The main hydrolysis is at the same liquor-to-wood ratio with 40 percent hydrochloric acid at 35°C (95°F) for 180 minutes followed by a posthydrolysis step with 2 percent hydrochloric acid at 110°C (230°F) for 60 minutes. The xylose solution in the furfural reactor requires 3 percent hydrochloric acid at 195°C (383°F) for 1.1 minutes.

The plant capacity is 1,005 tonnes (1,108 tons), dry basis, per day. Product capacity is 88.6 million litres (23.4 million gallons) per year of ethanol, 35 million kilograms (77.3 million pounds) per year of furfural, 15.5 million kilograms (34.1 million pounds) per year of acetic acid, and 76.7 million kilograms (168.9 million pounds) per year of lignin residue. In addition, the plant annually requires 69.2 million kilograms (152.6 million pounds) hydrochloric acid, 106.3 kilograms (234.3 million pounds) lime, 14.3 million kilograms (31.6 million pounds) calcium chloride, 0.4 million kilograms (0.8 million pounds) phosphate, and 0.4 million kilograms (0.8 million pounds) urea. Steam consumption is 274,664 kilograms (616,000 pounds) of steam per hour and 11,800 kilowatts of electricity. Glucose to ethanol conversion efficiency is assumed to be 95 percent of theoretical efficiency, pentose to furfural is assumed to be 84 percent of theoretical efficiency, and acetic acid recovery is assumed to be 90 percent of theoretical efficiency.

Total capital investment is $93.6 million (1979). Annual total direct operating expenses are $33.4 million and total annual revenues are $74.5 million.

2. **IMPLEMENTATION FACTORS:** This process requires a large capital investment and a large, continuous wood supply. The design, construction, and operation requires careful selection of equipment and materials of construction and careful operation to operate and maintain a highly efficient hydrochloric acid recovery system. The acid cost is over 25 percent of the total operating expense and only 96 percent of the acid is recoverable. Of the recoverable acid, over 96 percent must be recovered to meet the market price of $0.43 per litre ($1.65 per gallon) ethanol (1979).

Sales of ethanol should not be a problem if the production cost is reasonable; but the sales of the furfural, however, could be a problem. The plant described produces over one-half of the annual United States needs of furfural. Market expansion would be necessary to provide continuing furfural sales at a price that would provide a profit for furfural production.

3. ENVIRONMENTAL FACTORS: Environmental effects are not discussed in the report. Raw material growing and harvesting can be done without serious environmental effects if enough land area is available. Wastewater disposal would require primary and secondary treatment to remove solids and chemical and biological oxygen demand. Air pollution from combustion of wood and lignin fuels can be controlled, but air pollution from escaping hydrochloric acid could be a serious problem if the plant is not carefully planned and operated.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No other research has been conducted in the process in recent years. Hydrolysis plants using this process (Bergius process) that operated at Mannheim and Regensburg, Germany, during World War II are described in The Chemical Technology of Wood, Chapter IV, by H. F. J. Wenzl, Academic Press, New York, N.Y., 1970.

5. OBJECTIVE OBSERVATIONS: The report shows that ethanol production cost is sensitive to the cost of material of construction for the equipment in contact with the hydrochloric acid. Teflon-coated stainless steel is recommended, but no information is given on its performance in concentrated and dilute hydrochloric acid. The process cannot be considered for commercial operation without being proven on a pilot scale.

6. SUBJECTIVE OBSERVATIONS: The process described requires high capital investment and has high operating costs. Favorable economics relies on sale of by-product furfural and lignin. Economic viability is also sensitive to the efficiency of acid recovery and material of construction costs. Markets for the quantity of furfural produced are not known. Likewise, the possibility of using the reactive lignin produced for any commercial product is not known, but yet the lignin is shown to have a market value. The Bergius process plants in Germany did not operate economically because of unfavorable acid recovery efficiency and corrosion. These two problems still persist for the process.

FERMENTATION TO ETHANOL

Detailed information and data on ethanol production from sugar crops are presented in:

Alcohol Fuels: Ethanol, Methanol and their Use. A State-of-the-Art Review. AID Office of Energy, Washington, D.C. (in preparation).

Selected information and data on ethanol fermentation are found in the entry statements presented in this section. The entry statement index, Table C-XV, is designed to aid readers in their search for specific data entries. The location of entry statements and the corresponding literature sources are indicated in Table C-XVI.

TABLE C-XV

ENTRY STATEMENT INDEX FOR ETHANOL FERMENTATION

Sources of Data (Countries):	
Australia	3
Brazil	5
Guatemala	4
U.S.	1,2,6,7
Data Type:	
Laboratory or bench-scale experiment	1,3,4
Pilot/demonstration tests	7
Commercial Systems	
- Small	6
- Large	2
General	
Biomass Feedstocks:	
Sugary Feedstocks	
- Sugarcane	4,5
- Molasses	2,5
- Sugar beets	3
Grains (corn, milo, wheat, etc.)	2,6
Cellulosic feedstock (i.e., wood, crop residue, etc.)	1
Starch crops	7

TABLE C-XVI

SOURCE AND LOCATION OF ENTRY STATEMENTS

Entry Statement Number and Page		Literature Source
1	C-803	"Dehydratation of Ethanol: New Approach Gives Positive Energy Balance," M. R. Ladisch and K. Dyck, Science, vol. 205, 1979, p. 898.
2	C-804	"Low Energy Distillation Systems," R. Katzen et al., paper presented at the American Chemical Society Meeting, San Francisco, U.S., August 1980.
3	C-805	"Production of Fuel Ethanol by Solid-phase Fermentation," K. D. Kirby and C. J. Mardon, Biotechnology and Bioengineering, vol. 22, 1980, p. 2425.
4	C-806	"Ethanol from Sugarcane: EX-FERM Concept," C. Rolz, S. De Cabrera, R. Garcia, Biotechnology and Bioengineering, vol. 21, 1979, pp. 2347-2349.
5	C-807	"Alcohol Manufacture in a Sugar Factory," P. M. A. M. Chenu, International Society of Sugarcane Technology, Proceedings of ISSCT Congress, 2, September 1977, p. 3241.
6	C-808	"Preliminary Energy Balance and Economics of a Farm-Scale Ethanol Plant", D. Jantzen and T. McKinnon, Solar Energy Research Institute, SERI/RR-624-669R, Golden, CO., May 1980.
7	C-809	"Small-Scale Ethanol Production: Eight Case Histories" Solar Energy Research Institute, SERI/SP-733-713, Golden, CO., June 1980.

ENTRY STATEMENT NO. 1

1. VIABILITY FACTORS: Considerable energy and capital investment are expended in removing the last small percentage of water from ethanol prepared by fermentation and simple distillation. Results of recent laboratory experiments indicate the technical feasibility of removing water from aqueous ethanol by passing the vapor over dried starch, cellulose, or similar polysaccharides. These dried carbohydrates preferentially absorb water, allowing ethanol to distill over without need for azeotropic distillation. Using this method, aqueous ethanol with an initial concentration of about 13 percent has been concentrated to a final concentration of 99.0 percent. The total energy requirement with cellulose as dehydrating agent is reported to be 2,870 kJ per kilogram of alcohol (1,235 Btu per pound of alcohol). When compared with the conventional alcohol dehydration technique (i.e., azeotropic distillation), approximately 10 times less energy is consumed in the proposed dehydration technique. Calcium oxide (CaO) can be used instead of carbohydrates.

2. IMPLEMENTATION FACTORS: The experiments reported in this article have only been run on the scale of a few milliliters. Considerable laboratory work at bench scale (rather than microscale) will be required before the implementation of the process can be evaluated.

3. ENVIRONMENTAL FACTORS: The environmental problems caused by benzene, which is toxic, would be eliminated by use of this process.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: This process is intriguing but is of the type that may succeed well on a small scale but develops serious problems when large-diameter columns have to be packed with biomass materials. Such columns can develop channels and/or have mechanical problems when the column is not supported by nearby walls made of a sturdy material.

6. SUBJECTIVE OBSERVATIONS: This drying process is an example of a partially developed technology that could sidetrack a serious commercialization program in a developing country. Solid operating data at least at the pilot-plant scale involving columns at least 1 foot in diameter are needed before such technology could be transferred with any confidence to commercial usage. Of course, development of the process should have relatively high priority, but a firm distinction must be made between development activities and technology that is ready for usage.

ENTRY STATEMENT NO. 2

1. VIABILITY FACTORS: A primary consideration in all schemes for producing substitute liquid fuels lies in the energy consumed to produce the fuels. By energy re-use, pressure cascading, and waste heat recovery, the expenditure of energy in distillation (alcohol recovery) can be greatly reduced. Such energy savings have been industrially demonstrated in three systems described in this paper. For high-grade industrial ethanol production, a steam consumption of 3.0 to 4.2 kg/liter (25 to 35 lb/U.S. gallon) of 100°G.L. alcohol is realized. For motor fuel grade anhydrous alcohol, the steam consumption is 1.2 to 1.4 kg/liter (10 to 12 lb/U.S. gallon) of 96°G.L. alcohol.

The key features of this high quality alcohol distillation system are:

— Extractive distillation is used to remove impurities from the aqueous alcohol. This extractive distillation will reduce the fuel oils and lead concentrations in the final ethanol product to between 20 and 30 ppm. Azeotropic distillation is used to remove the last traces of water when making anhydrous alcohol.

— The use of pressure cascading permits substantial heat recovery and re-use. In this system the extraction tower and concentrating tower are operated at a pressure higher than the rectifying tower. The overhead vapors from these pressure towers supply thermal energy to rectifying tower reboilers. By operating in this manner, the steam usage is kept to a minimum. Commercial facilities using this pressure cascading technique, show steam usages of only 3.0 to 4.2 kg of steam per liter (25 to 35 lb/gal) of 96° G.L. (192° U.S. proof) ethanol compared to 6.0 kg/liter in earlier conventional system.

— Substantially all (95 to 98 percent) of the ethanol in the crude feed is recovered as a first-grade product.

2. IMPLEMENTATION FACTORS: This efficient ethanol distillation system has been commercially proven, and it is successfully operated with four different fermentation feedstocks, namely, molasses, grain (corn or milo), corn wet milling middlings, and sulfite waste liquor. However, the highly advanced control system used in this process could affect its implementation in the environment of a developing country.

3. ENVIRONMENTAL FACTORS: Although this distillation system reduces energy consumption, no improvement is made in the production of liquid effluents (stillage) which is the major environmental concern.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: Because of its low fuel consumption, this system makes possible the use of additional sugar crop bagasse for fuels, chemicals, cattle feed, etc.

6. SUBJECTIVE OBSERVATIONS: Implementers should not expect to obtain the optimum mentioned in this paper (1.8 to 2.4 kg of steam/liter of alcohol or 15 to 20 lb of steam/gallon), but the system does appear to be highly effective.

ENTRY STATEMENT NO. 3

1. VIABILITY FACTORS: A method for obtaining relatively concentrated ethanol solutions directly from chopped or pulped sugar beets by fermentation with yeast in the absence of added water is described. The beets are reduced to 3 to 5 mm particles (0.11 in to 0.19 in.) and charged to the fermenter. The pH is adjusted to 4.5. A 10 percent suspension of bakers yeast is added and the solid pulp is allowed to ferment anaerobically at 25°C to 30°C (77°F to 86°F) without the addition of water. The reaction is complete in approximately 16 hours. The fermented pulp is pressed to remove the fiber from the juice which contains both the yeast and ethanol. The yeast is separated centrifugally, and the ethanol is recovered by distillation. The reaction has been run on a laboratory scale up to 1 kg (2.2 lb) of beets per experiment. Squeezing the ethanol solution from the beets is much more effective than squeezing sugar from the beets and then fermenting.

Laboratory yields of 92 percent of the theoretical ethanol have been obtained. Based on $15 per tonne ($13/ton) sugar beets, ethanol production at $0.28 per liter ($1.06/gal) is claimed.

2. IMPLEMENTATION FACTORS: For geographical areas where sugar beets can be grown, this process holds promise for reduction in the capital investment in preparing beets for fermentation, fermenting them, and distilling them. The authors claim that quite simple equipment can be used for much of the processing and that the process is especially amenable to small quantities of starting material.

3. ENVIRONMENTAL FACTORS: The environmental problems associated with stillage are likely to be relatively small in that ethanol concentrations are high (9 percent or more). If the ethanol were made locally in small units, simple spray irrigation of fields might be practiced.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: None.

5. OBJECTIVE OBSERVATIONS: The initial data appear quite attractive, but caution should be exercised in extrapolating from 1 kg (2.2 lb) to a larger scale. For example, the heat released in fermentation is considerable, and a large pile of beets could generate enough heat either to stop the fermentation by killing the yeast or to produce spontaneous combustion.

6. SUBJECTIVE OBSERVATIONS: This concept is intriguing and merits a high priority in research and development in geographical areas where beets can be grown. However, it is exactly the type of superficially appealing process that could cause problems if the entire concept is not subjected to scrutiny to identify flaws and correct them.

ENTRY STATEMENT NO. 4

1. VIABILITY FACTORS: Preliminary information is presented on production of ethanol directly from chipped sugarcane pieces that have not been subjected to energy-intensive milling operations. The intention is to reduce the capital investment required for grass-roots ethanol facilities and to reduce the energy consumption in operating heavy mechanical equipment. The principle of the EX-FERM (extraction and fermentation) process is that the cells do not need to be crushed for sugar to migrate into the fermentation medium—they can diffuse into the medium.

A cutter removes foliage and feeds clean cane billets to either a Tilby separator or a wood chipper. The pith coming from the separator has an apparent bulk density between 0.27 and 0.32 grams per cm^3 (0.009 to 0.010 lb/in^3), and chips have a value between 0.42 and 0.44 grams per cm^3 (0.015 to 0.016 lb/in^3). The particle size ranges from 0. 48 to 1.0 centimeter (0.18 to 0.40 in). Part of the sucrose-rich pith or chips are dried and stored to operate during the off-season when cane is not available. Fermentation proceeds with either fresh or dried material when boiling water is added in a ratio of 1 to 1.4 by weight. The mixture is cooled to 30°C (86°F) and inoculated with yeast. A two-cycle operation yields a solution containing approximately 5 percent ethanol.

2. IMPLEMENTATION FACTORS: The process, if it can be implemented on a commercial scale, provides for a reduced capital investment and opportunities to store material for the off-season.

3. ENVIRONMENTAL FACTORS: The environmental problems associated with stillage are not reduced by the EX-FERM process. The problem is aggravated by the fact that the ethanol solutions to date are more dilute than with conventional fermentation, and therefore, the stillage would be more difficult to treat by concentration or similar techniques.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: The EX-FERM process and related processes are developments that are concerned with key problems in the construction of grassroots plants for reasonable capital investments in developing countries. There is insufficient data presented here to permit commercialization, but the data are sufficiently attractive to merit resolution of the technical issues so that commercialization can proceed.

6. SUBJECTIVE OBSERVATIONS: As with all new technology, engineering problems can be expected in the first commercializations. However, premature commercialization of the process before it has been demonstrated on a sufficient scale should be avoided.

ENTRY STATEMENT NO. 5

1. VIABILITY FACTORS: The alcohol technology used by Copersucar, a large sugar cooperative in Brazil, is described. The alcohol plants are associated with raw sugar production units. Final molasses is converted into ethanol and the molasses is supplemented with sugar cane juice as required by the needs of the raw sugar market and of the alcohol market. Molasses is produced at the rate of 30 to 40 kg per tonne (60 to 80 lb/ton) of cane in Brazil, and fermentation of this molasses (diluted with water) using the conventional Mello's discontinuous process yields about 12 L (3 U.S. gal) of ethanol. This fermentation process is conducted for approximately 12 to 16 hours at high yeast concentration. The product alcohol is recovered and dehydrated using conventional distillation and rectifying systems. The overall yield of ethanol is about 90 percent of theoretical yield. Low-pressure (0.6 to 1 kg/cm^2 or 8.5 to 14.0 lb/in^2) exhaust steam from the sugar factory prime movers is used for supplying heat energy to the distillation columns. Steam consumption varies from 3.5 to 5.5 kg/L (24 to 46 lb/U.S. gal) of alcohol produced. Total water consumption in the fermentation plants is about 141 L/L (141 gal/gal) of alcohol produced. The total electric consumption is about 0.05 kWh/L (0.19 kWh/gal) of alcohol produced. When cane juice, instead of molasses, is diverted to the fermentation plant, about 67 L of alcohol are produced per tonne of cane (16 gal/ton). This is equivalent to 600 L of ethanol per tonne (144 gal/ton) of crystallizable sugar, if it is diverted to the fermentation plant.

2. IMPLEMENTATION FACTORS: The association of a fermentation plant with an existing sugar factory improves the economics of ethanol production by not having to invest in front-end juice extraction and feedstock transportation operations. Also, most of the utility needs of the fermentation plant can be supplied by the exhaust steam from the sugar factory. The Brazilian government fixes the price of ethanol. in accordance with the sugar price to avoid any loss of revenue to those factories that transform sugar into alcohol.

3. ENVIRONMENTAL· FACTORS: The "slop" (i.e., stillage) or effluent stream produced in the fermentation plant is sent to the cane fields as fertilizer. This is either pumped to neighboring fields or carried to remote fields in motor tankers and sprinkled.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: None.

5. OBJECTIVE OBSERVATIONS: Considerable practical information is presented concerning the contamination problems that arise when, for example, yeast is recycled. Good information is also presented on yields at various stages of the fermentation and distillation process. However, there also are many omissions and a lack of statistical data on day-in, day-out operations, which this large sugar cooperative no doubt has. The "slop" (i.e., stillage) that causes environmental damage in Brazil is not mentioned.

6. SUBJECTIVE OBSERVATIONS: It is rare that those who are deeply involved in production take time to provide really practical information. This article should be read by those contemplating building ethanol facilities and researchers contemplating improving on the classical process.

ENTRY STATEMENT NO. 6

1. **VIABILITY FACTORS:** The report describes a small-scale ethanol plant designed, built, and operated by a farmer family in Campo, Colorado, U.S. The plant was built to provide an alternative market for the grain sorghum produced on the farm. The plant processes about 4,200 metric tons (160,000 bushels) of grain per year and produces about 1.5 million liters (400,000 gallons) of 190-proof (95 percent) ethanol per year.

The plant comprises two 13,200-liter (3,500-gal) cookers with agitators, three 26,500-liter (7,000 gal) fermenter tanks with agitators, three 4.9- meter (16 ft) sieve-tray distillation columns and two steam generators with waste heat recovery coils. Cookers and fermenters operate batch-wise on 36-hour cycles. Two cooked batches are required per fermentation batch; distillation is continuous.

About 3.3 tons (124 bu) of grain are heated to 88°C with an enzyme and agitated for 1.5 hours. The batch is then pumped into a fermentation tank with saccharifying enzyme and yeast. Fermentation takes about 36 hours at 45°C with continuous agitation. After fermentation, the beer solution contains about 12 percent ethanol. Ethanol is distilled to 190 proof (95 percent). The cooled stillage is divided into a solid-products fraction of about 65 percent moisture and a thin stillage containing about one-third of the solids. The solids fraction which contains 28 to 32 percent protein (dry basis) is sold to livestock growers as a protein supplement. The stillage is not used at present.

The plant is characterized by a high-energy efficiency achieved through recovery of waste heat at various stages of the process. Diesel fuel and electricity are the two sources of energy. Ethanol production requires about 8,000 kJ/L (about 29,000 Btu/gal) of which about 22 percent is in the form of electricity. The net energy ratio (ratio of energy content of ethanol to energy inputs) is about 2.8, excluding energy for farming the grain and energy credits for the stillage. Operation of the plant requires one operator full time.

The capital cost of the plant is $400,000 (1980 dollars) or about $0.27 per liter of annual capacity ($1.00 per gallon of annual capacity). For grain priced at $70 per ton ($1.90 per bushel), diesel fuel at $0.29 per liter ($1.10 per gallon), electricity at $0.05 per kWh and a credit for stillage of $0.05 per kg of grain processed, the production cost of ethanol is estimated at $0.32 per liter ($1.20 per gallon).

2. **IMPLEMENTATION FACTORS:** It is intended to upgrade the plant to produce 200-proof (100 percent) ethanol by using molecular-sieve drying columns. With this improvement, it is estimated that the plant should provide a 35 percent return on investment after taxes. This estimate was based on a selling price of $0.50 per liter ($1.90 per gallon) for anhydrous ethanol.

3. **ENVIRONMENTAL FACTORS:** No mention is made of environmental problems associated with the disposal of the thin stillage.

4. **RELATED PAPERS AND SUGGESTED FURTHER READING:** "Small-Scale Ethanol Production: Eight Case Histories", Solar Energy Research Institute, SERI/SP-733-713, Golden, CO, June 1980.

5. **OBJECTIVE OBSERVATIONS:** The economics of the plant are very sensitive to the price of grain, the selling price of stillage, and the selling price of ethanol fuel. The recent drop in gasoline prices recorded in the U.S. (1982) probably make the plant economically less attractive.

6. **SUBJECTIVE OBSERVATIONS:** None.

ENTRY STATEMENT NO. 7

1. VIABILITY FACTORS: An experimental plant was set up in a North Dakota farm cooperative to produce ethanol from cull potatoes. The plant includes a 10-horsepower hammer mill to grind the potatoes before cooking, an 11,000-liter (3,000-gallon) jacketed tank serving as cooker, fermenter and pot for the distillation column and a 0.3 meter (12 inches) in diameter, 4.9 meter (16 feet) high distillation column. The distillation column is made of galvanized, corrugated culvert pipe packed with 1.2 centimeter (0.5 inch) ceramic saddles. Energy for cooking and distillation is provided by electric immersion heaters built by the cooperative. Off-peak electricity is used to operate the plant. The plant operates batch-wise and requires about 120 hours for the treatment of a batch (from grinding to distillation). The maximum distillation capacity is about 16 gallons per hour (about 60 liters per hour). Each batch produces about 750 liters (about 200 gallons) of 175 proof (87.5 percent) ethanol. The average yield is about 1 liter of 200-proof (100 percent) equivalent ethanol per 12 kilograms of potatoes (1.0 gallon per hundred weight). The energy required for ethanol production is about 4.8 kWh per liter (18 kWh or 61,000 Btu per gallon) of 175-proof ethanol. Operations require 1 to 2 operators for grinding, 1 operator for cooking and 1 to 2 operators for distillation.

The capital cost was about $15,000 for materials and equipment and about $30,000 for labor.

2. IMPLEMENTATION FACTORS: The plant has operated since 1979 on an experimental basis. The fuel produced, 175-proof ethanol, was successfully tested in a home heating system and in a 8 horsepower snow blower. The designer of the plant suggests that stainless steel be used in the distillation column and that more automatic temperature controls be used to reduce the operating man power. After some more testing, the experimental plant will be shut down, having served its purpose of providing realistic evaluation data for the farm cooperative.

3. ENVIRONMENTAL FACTORS: No environmental problems associated with discarding the stillage are mentioned.

4. RELATED PAPERS AND SUGGESTED FURTHER READING: No related papers.

5. OBJECTIVE OBSERVATIONS: This experimental plant is an illustration of a small-scale unit built with available materials and labor. More data concerning its design, construction, and operation should be obtained. The problem of utilization and/or discarding of the stillage should be further investigated.

6. SUBJECTIVE OBSERVATIONS: None.

SECTION D

PETROLEUM DERIVED ENERGY CONSUMPTION AND BIORESOURCE AVAILABILITY DATA

This section contains tables illustrating the format for the presentation of petroleum-derived energy consumption and bioresource availability data for USAID countries. One country, Ecuador, is used as an example.

Several contractors are collecting these data for USAID countries. As this data gathering is completed, tables containing statistical information on USAID countries will be made available for inclusion in this handbook.

The statistical data on petroleum-derived fuel consumption and bioresource availability are intended for the users who are not familiar with a country's energy situation and have not selected a particular sector/petroleum-derived fuel for potential bioenergy substitution. These data will help the user in selecting an energy intensive sector and corresponding petroleum-derived fuel.

Table D-I presents the format for a country data index designed to guide users to relevant tables containing statistical information on a particular country. Table D-II illustrates the format for presenting petroleum-derived fuel use patterns by sector—residential, transportation, industrial, and electricity generation—for Ecuador. Typical petroleum-derived fuels are: gasoline, diesel oil (also distillate oil), kerosene, residual fuel oil (heavy fuel oil), and liquified petroleum gas (LPG). Similarly, Tables D-III illustrates the format for presenting biomass production data for Ecuador. The general categories of biomass resources are agriculture and forest, both crop and residue; aquatic plants; marine plants; manures; and refuse (urban solid waste/sewage sludge). Biomass resource data will be presented both in dry tonnes and barrels of oil equivalent. The oil equivalency will be determined by comparing the higher heating value of biomass resource with the average higher heating value of crude oil. It should be noted, however, that a unit of energy contained in crude oil is more useful than a unit contained in biomass resource.

TABLE D-I

COUNTRY DATA INDEX

COUNTRY	PAGE NUMBER FOR PETROLEUM-DERIVED ENERGY CONSUMPTION PATTERN	BIORESOURCE AVAILABILITY
Ecuador	D-4	D-5

TABLE D-II

PETROLEUM-DERIVED FUEL USE PATTERN, ECUADOR
1,000 metric tonne (1,000 bbl)

SECTOR TYPE OF FUEL*	RESIDENTIAL	TRANSPORTATION	INDUSTRIAL[1]	ELECTRIC GENERATION
Gasoline	(9.9)	(116.6)	--	--
Diesel oil (distillates)	--	(37.8)	(56.9)	--
Kerosene	(26.6)	(14.7)	(5.0)	--
Residual fuel oil (bunker oil)	--	(24.3)	(31.0)	(15.6)[2]
LPG (liquified petroleum gases)	78.5	--	1.9	--

*See the Bioenergy Fuel Substitution Index and Directory for potential biomass-derived fuel substitutes.

1. Includes industrial sector, agricultural sector, fishing and public services.

2. Assumes all fuel used for electricity generation is residual fuel oil.

TABLE D-IV

BIOMASS PRODUCTION, ECUADOR
1,000 metric tonnes (1,000 bbl)

PRODUCTION	RESIDUE[1]		CROP	
BIOMASS SOURCE TYPE*	1,000 metric tonnes (1,000 tons)	oil equivalent 1,000 metric tonnes (1,000 bbl)	1,000 metric tonnes (1,000 tons)	oil equivalent 1,000 metric tonnes (1,000 bbl)
Agriculture				
Starch	--	--	--	--
Sugar	--	186	--	--
Cellulose	--	52.1	--	--
Forests	--	72.7		
Aquatic plants	--	--	--	--
Marine plants	--	--	--	--
Manures/sewage	--	--	--	--
Refuse (urban solid wastes)	--	--	--	--

*See Table III, "Fuels Derived from Biomass Resources," for potential biomass-derived fuels.

1. Residues from Agroindustries.

Source: G. Beinhart and J. F. Henry, Biomass for Energy in Ecuador: an Assessment, Report to USAID, Washington, D.C., January 1981.

GLOSSARY

Acid gases - carbon dioxide (CO_2) and hydrogen sulfide (H_2S) gases.

Adiabatic - any process where heat is neither given off nor absorbed.

Aldehyde - any of highly reactive organic chemical compounds characterized by the common group CHO.

Anaerobic Digestion - biological digestion of biomass feedstocks in the absence of oxygen.

Aromatics - a cyclic hydrocarbon containing one or more six-carbon (benzene) rings.

Atomizer - a device which divides a liquid into extremely minute particles, either by impact with a jet of steam or compressed air, or by using some mechanical power.

Bacteria - any of numerous unicellular microorganisms occurring in a wide variety of forms.

Baghouse - chamber in which dust (particulate matter) from flue gases is separated by fabric filters.

Bench-scale Unit - a small-scale laboratory unit for testing process concepts and operating parameters as a first step in the evaluation of a process

Bioenergy - fuels and energy products derived from biomass resources.

Sources:

1. "Energy Reference Handbook," edited by Sullivan, T.F., Government Institute Inc., Washington, D.C., November 1977.

2. "The American Heritage Dictionary of the English Language," edited by Morris, W., Houghton Mifflin Company, 1976.

Biogas - a mixture of methane (CH_4) and carbon dioxide (CO_2) produced by the anaerobic digestion of biomass feedstock.

Biological Oxygen Demand (BOD) - a measure of the amount of oxygen consumed in the biological processes that break down organic compounds in water.

Biomass - biological resources such as wood, wood waste, agricultural residue, animal manure, municipal solid waste, etc.

Catalyst - a substance that accelerates the rate of a chemical reaction without itself undergoing a permanent chemical change.

Cetane Number - a performance rating of a fuel with respect to its ability to self-ignite, a high cetane number indicates good self-ignition characteristics.

Cellulose - a carbohydrate polymer, $(C_6H_{10}O_5)_n$, the main constituent of all plant tissues and fibers.

Centrifuge - an apparatus rotating at high speed which utilizes the centrifugal force generated to separate materials of different densities.

Char - the solid residue remaining after the removal of moisture and volatile matter from biomass feedstocks.

Combined Cycle - two sequential thermodynamic power conversion systems operating at different temperatures.

Cracking - the partial decomposition of high-molecular-weight organic compounds into lower-molecular-weight compounds, generally as a result of high temperature.

Cyclone Separator - essentially a settling chamber to separate solid particles from a gas, in which gravitational acceleration is replaced by centrifugal acceleration.

Diesel Fuel Oil (and Distillate Oil) - a brownish-colored liquid fuel obtained by the distillation of crude petroleum oil.

Digestible Fraction - fraction of biomass feedstock which can be converted by bacterial action.

Distillation - a process of vaporizing a liquid and condensing the vapor by cooling; used for separating liquids into various fractions according to their boiling points or boiling ranges.

Emulsion - a suspension of small globules of one liquid in a second liquid with which the first will not mix.

Entrained-bed - a bed in which solid particles are suspended in a moving fluid and are continuously carried over in the effluent stream.

Enzyme - living microorganisms functioning as biochemical catalysts.

Exothermic Reaction - a chemical reaction in which heat is liberated.

Fatty acids - any of a large group of organic acids having the general formula $C_nH_{2n+1}COOH$.

Fixed-bed - a bed of stationary solid particles in intimate contact with fluid passing through them.

Flammability - ease of ignition of a gaseous or liquid fuel.

Fluidized-bed - a bed of solid particles maintained in balanced suspension against gravity by the upward motion of a gas.

Gasoline - a refined, colorless, liquid fuel which, by its composition, is suitable for use as a fuel in internal combustion engines.

Gum - a viscous organic polymeric substance.

Heating Value - the amount of heat produced by the complete combustion of a unit quantity of fuel. Heating value is reported on two bases: higher heating value with liquid water as the product and lower heating value with gaseous water as the product. The difference between the two values equals the latent heat of vaporization of the water of combustion.

Hemicellulose - a carbohydrate polymer containing five carbon atom sugar molecules; associated with cellulose in plant matter.

Hog Fuel - wood waste produced as a result of forest products industry operation, which has been reduced in size in a mill commonly called a "hog".

Hot Carbonate Process - a process used for removing carbon dioxide from a gaseous steam.

Hydrocarbon - a compound that contains only hydrogen and carbon. The simplist and lightest forms of hydrocarbon are gaseous with greater molecular weights; they are liquid, while the heaviest are solids.

Hydrocracking - the combination of cracking and hydrogenation of organic compounds.

Hydrogenation - chemical reactions involving the addition of gaseous hydrogen to a substance in the presence of a catalyst under high temperatures and pressures.

Leachate - the liquid that has percolated through the soil or other medium.

Lignin - a major noncarbohydrate fraction of wood containing poly-romatic compounds.

Lignocellulose - biomass feedstocks containing lignin and cellulose in combination.

Liquified Petroleum Gases (LPG) - a hydrocarbon gaseous mixture containing propane and butane, which can be liquified under moderate pressure at normal temperatures.

Loading Rate - the rate of biomass feed input per unit volume of a conversion equipment.

Mesh Size - measure of fineness of a screen, i.e., a 200-mesh sieve has 200 openings per linear inch.

Municipal Solid Waste - solid waste or trash collected in the urban and suburban areas.

Natural Gas - naturally occuring mixtures of hydrocarbon gases and vapors, the major component being methane.

Newtonian - fluids whose viscosity is a linear function of their physical properties.

Night Soil - human excrement collected for use as fertilizer.

Nutrient - something that aids in the growth of certain organisms.

Octane Number - a term indicating the ability of a fuel to resist self-ignition at high pressures; higher the octane number of a fuel, better its ability to resist self-ignition.

Olefin - a class of hydrocarbons containing one or more double bands and having the general chemical formula C_nH_{2n}.

Organic - being, containing, or relating to carbon compounds, especially in which hydrogen is attached to carbon whether derived from living organisms or not.

Oxidant - any oxygen-containing substance that reacts chemically in the air to produce new substances.

Paraffin - a group of hydrocarbons having no carbon double bands and with a general chemical fromula C_nH_{2n+2}.

Parasitic Power - power required to run in-plant machinery.

Pilot-scale Plant - a chemical process plant containing all the processes of commercial unit, but on a smaller scale, for the purpose of studying the techncical and economic feasibility of the process.

Power Cycle - a sequence of steps in which the energy contained in a working fluid is converted to useful mechanical power.

Reforming - a process in which low-grade or low-molecular-weight hydrocarbons are catalytically converted to high-grade or higher-molecular-weight materials; also applies to the breaking of methane to hydrogen and oxides of carbon, in the presence of steam and a catalyst.

Residual Fuel Oil (or Heavy Oil) - the heavier, high viscosity fuel oil obtained as a distillation residue of crude oil refining process.

Retention time - the average length of time a biomass feed particle spends in a biogas digester.

Retrofit - modification of existing energy conversion system to burn other low grade fuels.

Saturated Steam - steam leaving the boiler at the boiling temperature of water corresponding to its pressure.

Shaft Work - mechanical work produced by the shaft of a turbine.

Shift Reaction - a catalytic reaction between carbon monoxide and steam to produce hydrogen.

Slag - molten ash from wood or other biomass feedstock composed primarily of inorganic salts.

Slurry - a suspension of pulverized solid in a liquid.

Soot Blower - device used to clean ash particle deposits from tubes and furnace surfaces; steam and compressed air is generally used for cleaning.

Stoichiometry - the definite proportions in which molecules react chemically to form new molecules.

Superheated Steam - steam leaving the boiler at temperatures higher than the boiling temperature of water at a particular pressure.

Trommel - a revolving cylindrical sieve used for sizing rock and ore.

Volatile Solids - the fraction of dry biomass feedstock given off as gas and vapor when heated to a certain specified temperature in the absence of air.

Waste Stabilization - use of bacteria to remove the pollution hazards of certain waste steam.

Zeolite - any of a group of approximately 30 hydrous aluminum silicate minerals or their corresponding synthetic compounds, used chiefly as molecular filters and ion exchange agents.

Superheated Steam - steam leaving the boiler at temperatures higher than the boiling temperature of water at a particular pressure.

Trommel - a revolving cylindrical sieve used for sizing rock and ore.

Volatile Solids - the fraction of dry biomass feedstock given off as gas and vapor when heated to a certain specified temperature in the absence of air.

Waste Stabilization - use of bacteria to remove the pollution hazards of certain waste steam.

Zeolite - any of a group of approximately 30 hydrous aluminum silicate minerals or their corresponding synthetic compounds, used chiefly as molecular filters and ion exchange agents.